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The Journal of

THE ROYAL AERONAUTICAL SOCIETY

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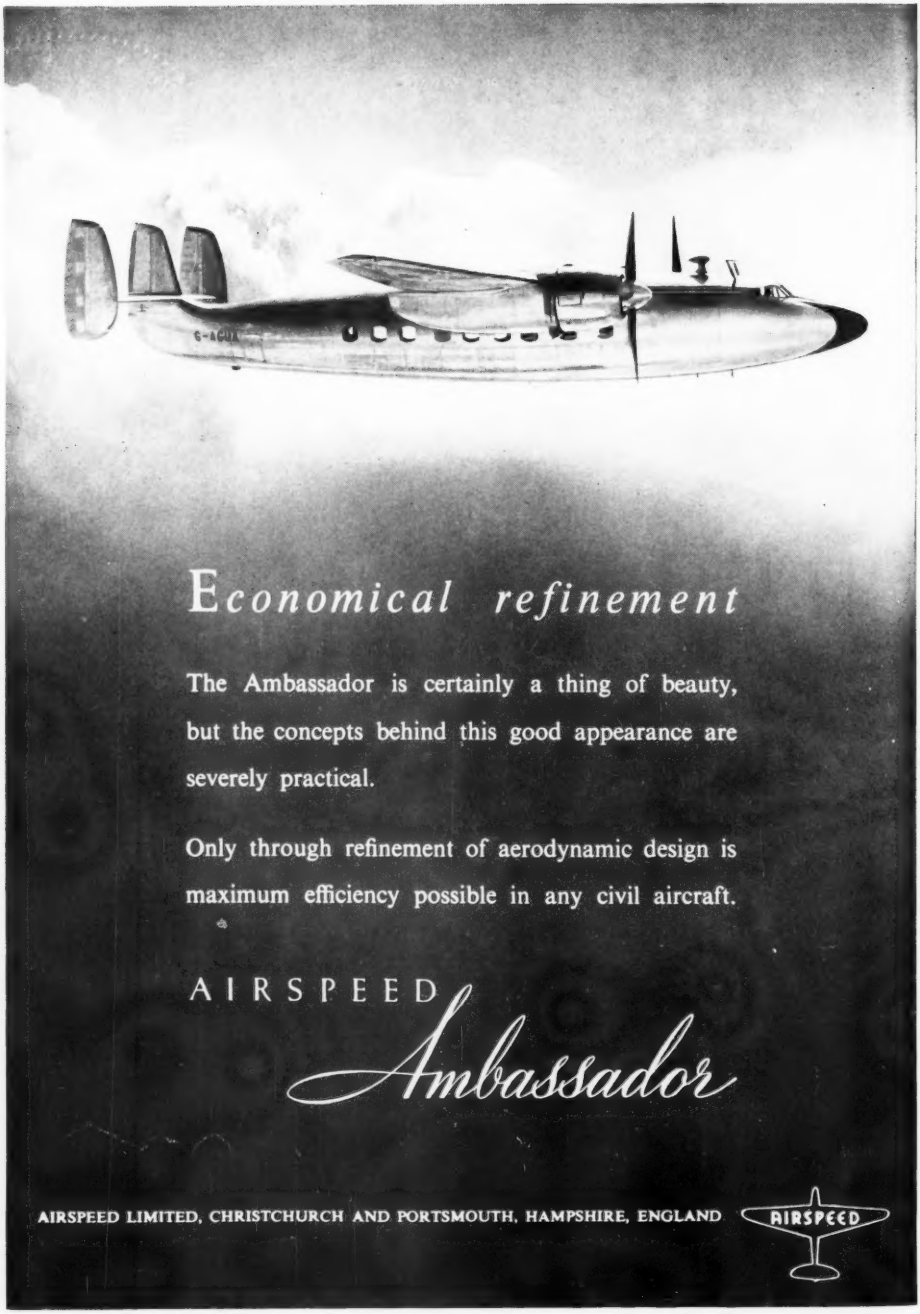

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THE ROYAL AERONAUTICAL SOCIETY
4 HAMILTON PLACE, PICCADILLY, LONDON, W.1

JANUARY NOTICES 1948

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members (or non-members) will contribute papers on their own special subjects.

NEW YEAR

The President and Council extend to all members at home and overseas their best wishes for the year 1948.

CONTENTS OF JANUARY JOURNAL

Problems of High Temperature Alloys for Gas Turbines, by Sir William T. Griffiths, D.Sc., F.R.I.C., F.Inst.P., F.I.M.

Some Recent Developments in the Landing Gear Field, by Captain R. Lucien, A.F.R.Ae.S.

Enemy Jet History, by D. R. Maguire, B.A., A.R.Ae.S.

RECEPTIONS—17th JANUARY and 24th JANUARY 1948

Receptions will be held by the President, Dr. H. Roxbee Cox and Mrs. Roxbee Cox, supported by the Council, from 3 to 6.30 p.m. at 4 Hamilton Place, on **Saturday, 17th January 1948** and **Saturday, 24th January 1948.** Many of the most interesting parts of the Hodgson-Cuthbert Collection and other rare aeronautical prints and books owned by the Society will be on exhibit and tea will be provided. An application form for tickets has already been sent to members. Tickets, 4s. each (not more than three guests per member) are obtainable from 4 Hamilton Place.

MEMBERS' SUBSCRIPTIONS

At the Special General Meeting held on 23rd October 1947, a Postal Ballot was called for, under the rules, to consider the proposals for an increase in the subscriptions. Out of 4,295 voting members of the Society (Founder Members, Fellows, Associate Fellows and Associates) 1,979 voted as follows: For the proposed increase in annual subscriptions 1,386; against the proposed increases 593.

The new rates of subscription are as follows:—

	Home			Abroad		
	£	s.	d.	£	s.	d.
Fellows	5	5	0	4	4	0
Associate Fellows	4	4	0	3	3	0
Associates	*3	3	0	*3	3	0
Graduates (aged 21-25)	2	2	0	2	2	0
Graduates (aged 26-28)	2	12	6	2	12	6
Students (aged under 21)	1	1	0	1	1	0
Students (aged 21 and over)	1	11	6	1	11	6
Companions	3	3	0	3	3	0
Founder Members	2	2	0	2	2	0

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The amounts of Entrance and Transfer Fees are unchanged.

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the Journal, and in this case his subscription will be reduced by £1 1s. 0d.

It will avoid delay and confusion when sending remittances for subscriptions if members will state their name clearly and give their grade of membership and address, please.

REVISED SYLLABUS FOR ASSOCIATE FELLOWSHIP EXAMINATION

The Revised Syllabus has been approved and will come into operation in two stages.

Part I of the examination becomes operative on 1st January 1949.

Parts II and III of the examination become operative on 1st January 1950.

The last examination under the present syllabus will be held during December 1949, and until then candidates can take the examination under either syllabus. Candidates who have not completed the examination under the present syllabus at that time will not be allowed to continue the examination under these conditions but will be granted exemption under the new conditions in the subjects of Part I which have been passed.

A revised list of exempting examinations will come into operation with the new syllabus on 1st January 1950.

The present syllabus is now *out of print*, but copies of the syllabus for *individual* subjects will be supplied to candidates on request.

ROYAL SOCIETY

The Council of the Royal Society have appointed Sir Frederick Handley Page to represent the Royal Aeronautical Society on the General Board of the National Physical Laboratory.

ANGLO-AMERICAN AERONAUTICAL CONFERENCE, SEPTEMBER 1947

A number of members have made enquiries regarding photographs taken at Guildhall during the dinner on 9th September 1947. A complete set is available for inspection at the offices of the Society and copies may be bought at 2s. 6d. per photograph.

GAS TURBINE ACCESSORY SYSTEMS by O. N. LAWRENCE, A.F.R.Ae.S.—

Summary of Lecture to be given at a joint meeting with the Institute of Fuel on Thursday, 15th January 1948.

The paper begins with a statement of the requirements of a Fuel System for these engines. A summary of engine types and their various characteristics follows. A brief description of the principles of control, and the way they can be applied to units, completes the first half of the paper. The second half relates to the problems connected with Starting and the different systems that can be used including Cartridge Starting.

THE AERODYNAMICS OF THE GAS TURBINE by A. R. HOWELL, M.A.—

Summary of Lecture to be given on Thursday, 12th February 1948.

Aerodynamics is naturally associated with the external air flow past aircraft, but with the advent of the gas turbine, it has also become of the greatest importance for the internal flow through such engines. The efficiency and bulk of the compressor and turbine components in gas turbines are largely an aerodynamic matter, and their design is determined

by a knowledge of the lift coefficients, drag coefficients, Mach Nos., etc., that can be used. The same fundamental laws, if they were fully known, would of course apply to both internal and external flows, but there are at present considerable differences in practice between the data obtained, and the detail methods used, for the two categories of flow. This lecture attempts to cover in a general way the internal aerodynamic flow through gas turbines.

In the lecture the emphasis has been placed on cascade investigations, axial compressors, turbines, starting with the two-dimensional flow past cascades of the blade elements and then considering where the flow is different in the actual compressor or turbine. Centrifugal compressors and ducting problems are dealt with briefly. The subject matter covers the design and characteristics of the components in addition to the more fundamental aspects of the flow; and although the lecture is mainly concerned with internal flow through aircraft gas turbines, some comparisons are made with other applications and with the external flow past aircraft. Reference is also made to published Continental and American practice on the aerodynamics of compressors and turbines.

LECTURE PROGRAMME—1948

The Lectures will be held at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, S.W.1 (by permission of the Council of the Institution) unless otherwise stated. Tea will be served at 5.30 p.m.

Visitors are welcome, but should obtain tickets through a member of the Society.

Thursday, 15th January 1948—Joint lecture with the Institute of Fuel. Gas Turbine Accessory Systems, by O. N. Lawrence, M.A., A.M.I.Mech.E., A.F.R.Ae.S.

Thursday, 29th January 1948—The Flight Testing of Helicopters, by W. Stewart, B.Sc.

Thursday, 12th February 1948—The Aerodynamics of the Gas Turbine, by A. R. Howell.

Thursday, 26th February 1948—The Evolution of the Design of an Aeroplane, by Professor R. L. Lickley, B.Sc., D.I.C., F.R.Ae.S.

Thursday, 18th March 1948—Flight Testing at High Subsonic Speeds, by H. Davies, B.A., M.Sc., A.F.R.Ae.S.

Saturday, 3rd April 1948—FULL DAY DISCUSSION ON SAFETY IN CIVIL AVIATION. Introductory Statements only will be made. Each will be followed by open discussion.

Morning Session

11 a.m.—Air Vice-Marshal D. C. T. Bennett, C.B., D.S.O., F.R.Ae.S., on The Economics of Safety.

12 noon—Professor A. A. Hall, M.Sc., M.A., F.R.Ae.S., on The Problems of Air Traffic Control.

1-2.30 p.m.—Luncheon Interval. Members and visitors should make their own arrangements for lunch.

Afternoon Session

2.30 p.m.—Dr. K. G. Bergin, M.A., M.D., M.B., B.Chir., M.R.C.S., L.R.C.P., A.F.R.Ae.S., on Physiological Aspects of Safety.

3.30 p.m.—General Discussion.

4.30-5 p.m.—Tea interval (tea provided).

Evening Session

5-6.30 p.m.—General Discussion and summing-up.

Thursday, 15th April 1948—The Aerodynamic Problems of High Altitude Design, by W. E. W. Petter, B.A., F.R.Ae.S.

Thursday, 27th May 1948—The 36th Wilbur Wright Memorial Lecture will be read by A. Gouge, B.Sc., F.R.Ae.S.

BELFAST BRANCH

Tuesday, 6th January 1948—Some Experiences in Experimental Gliding, Professor Hill, M.C., M.Sc., M.I.Mech.E., F.R.Ae.S.

Friday, 23rd January 1948—Smoking concert.

Tuesday, 3rd February 1948—High Speed Flight, Dr. Hilton.

Tuesday, 24th February 1948—Evening of lecturettes.

Tuesday, 16th March 1948—Inside Occupied Japan, William Courtenay, M.M., A.R.Ae.S.

All meetings are held at the Assembly Hall, Belfast College of Technology, at 7.30 p.m.

BRISTOL BRANCH

Tuesday, 20th January 1948—Debate.

Wednesday, 11th February 1948—The Design of a Large Naval Vessel, by H. S. Pengelley, R.C.N.C., M.Inst.N.A., Assistant Director of Naval Construction, Admiralty.

Monday, 23rd February 1948—Accidents and Their Investigation, by Air Commodore Vernon Brown, C.B., O.B.E., M.A., F.R.Ae.S., Accidents Investigation Branch, Ministry of Civil Aviation.

Wednesday, 3rd March 1948—Reading of Prize-winning Papers by Junior Members.

Monday, 22nd March 1948—Operation of Civil Transport Aircraft, by N. E. Rowe, C.B.E., F.R.Ae.S., Controller of Research and Long Term Development, British European Airways.

Wednesday, 14th April 1948—Film Night and Annual General Meeting.

All meetings will be held in the Conference Room, Bristol Aeroplane Co. Ltd., Filton House, at 6.0 p.m.

GLOUCESTER AND CHELTENHAM BRANCH

Thursday, 15th January 1948—Film on Rocket Flight (Sound track in English)—at Gloucester.

Wednesday, 4th February 1948 — Photographic Reconnaissance Operations, Group Captain R. C. Field—at Cheltenham.

Thursday, 4th March 1948—The Development of the A.S. Type Gas Turbine Engine, W. H. Lindsey, M.A., A.F.R.Ae.S.—at Gloucester.

Wednesday, 7th April 1948—Annual General Meeting followed by Film—at Cheltenham.

Gloucester meetings are held in the Wheatstone Hall, City Library, Brunswick Road, Gloucester, at 7.30 p.m. on *Thursdays*.

Cheltenham meetings are held in the Chemistry Lecture Theatre, Grammar School, Cheltenham, at 7.30 p.m. on *Wednesdays*.

LUTON BRANCH

Wednesday, 7th January 1948—Discussion Evening. Three papers will be read by members of the Branch and will be followed by discussions. Subjects: Aero-engines, Aircraft, Flying and Gliding.

Wednesday, 4th February 1948—Some Problems in Civil Aviation, by N. E. Rowe, C.B.E., B.Sc., D.I.C., F.R.Ae.S.

Both meetings will be held at the George Hotel, Luton, at 7 p.m.

MANCHESTER BRANCH

Thursday, 29th January 1948—Pressurisation, by G. Beardshall.

Thursday, 26th February 1948—Naval Aircraft, by Captain Fancourt.

Thursday, 1st April 1948—Flight Refuelling, by C. H. Latimer-Needham.

Meetings will be held at the Reynolds Hall, College of Technology, at 7.30 p.m.

PRESTON BRANCH

Wednesday, 7th January 1948—Problems of High Speed Flight, by D. L. Ellis, B.Sc., A.R.T.C., F.R.Ae.S. (Chief of Aerodynamics of the English Electric Company's Aircraft Division).

Wednesday, 28th January 1948—Photographic Interpretation of the Bomber Offensive against Germany, by S/Ldr. G. A. Morris, O.B.E. (formerly head of the Photographic Interpretation Section, H.Q., Bomber Command).

All lectures will be held, unless otherwise stated, at 7 p.m. in the Board Room of the Preston Chamber of Commerce, Fishergate, Preston (next to the Theatre Royal).

SOUTHAMPTON BRANCH

Wednesday, 7th January 1948—Rotating Wing Aircraft, by C. G. Pullin.

Wednesday, 4th February 1948—Structures Testing by P. B. Walker, M.A., Ph.D., F.R.Ae.S.

Lectures will be held at University College, Southampton, at 7 p.m.

GRADUATES' AND STUDENTS' SECTION

Tuesday, 20th January 1948—Films of the helicopter, lent by the Bell Helicopter Co. Commentary by Captain Cyril Turner, A.F.C., of Irvin-Bell Helicopter Sales Ltd.

Tuesday, 10th February 1948—Stability and Control Problems, by D. J. Lyons, Aero-Flight Section, R.A.E.

Wednesday, 25th February 1948—Suction Aerofoils, by B. Thwaites, Dept. of Aeronautics, Imperial College of Science and Technology.

Wednesday, 14th April 1948—The Influence of the Recent Civil Airworthiness Requirements on Civil Aircraft Design, by W. Tye, B.Sc., F.R.Ae.S., Air Registration Board.

Tuesday, 11th May 1948—The Light Aeroplane and the Future of Private Flying, by P. G. Masefield, M.A., F.R.Ae.S., Director General of Long Term Planning and Projects, Ministry of Civil Aviation.

All meetings will be held in the Library of the Royal Aeronautical Society, 4 Hamilton Place, W.1, at 7.30 p.m.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

JOURNAL BINDING

Because of increased costs, the prices of binding of Journals will be as follows:—

1947 Volume 15/-.

Previous Volumes 17/-.

Journals should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the office of the Society.

NEW MEMBERS

Associate Fellows

Douglas Edward Ackland (from Graduate), Phillip Brittain Aitken, James William Adderley, John Harry Clapham Atkins, Thomas Bancroft, Kenelm Joseph Godfrey Bartlett, Eric Victor Betts, Joseph Black (from Graduate), George Boyce, Stanley Charles Joseph Caliendi (from Graduate), Nevil John Eugene Chaplin (from Graduate), Mircea Michael Conea (from Graduate), Anthoney Michael Creedon (from Graduate), Ivan H. Driggs, John Dubbury (from Graduate), Reginald John Ford, Kee Poon Gan, George Denzil Gawthrope, John Hadji-Argyris, Arthur Barry Haines, Joseph Fletcher Harriman (from Associate), George Henry Hiscock, Lionel Russell Jenkins (from Graduate), John Menzies Kay (from Graduate), Fred Kirk, Tung-Hua Lin, Murray Parker McHeffey, Subramania Ramamritham, Fred Lees Robinson, Charles William Rossiter-Smith, Vernon Gerald Walker, John Charles Ward (from Associate), Norman Ralph Kenneth Wheatley, Norman Arthur White, Charles Horace Lionel Wynne.

Associates

John Sandford Balkwill, Leonard Logoz Bridgman, Frank Bright (from Student), Alan Harold Buchanan (from Companion), Frederick John Cable, Harry Cheers, William Bathie Cowan, William Herbert Douglas, Geoffrey Crosbie Jobling, Subandhu N. Majmudar, Alexander Maurice Raffael.

Graduates

Norman Frederick George Banfield, Hazel Marjorie Bigg, Jeffrey Laurence Crowder, Harry Frank Downton, Andrew James Duxbury (from Student), Ralph Gordon Evans, Sydney Kelsey, Ian Robert Lyon (from Student), William James Johnstone MacDonald, Alastair McKay (from Student), Pran Nath Malhotra, Alfred Charles Martin (from Student), Charles Albert Millidine, Basil Robert Edwin Riddaway, Robert James Ross (from Student), David Michael Scott, Walter Robert Stirling (from Student), John Keith Yates (from Student).

Students

Derek Watson Ashworth, Frederick Edward Baker, Antony John Barker, Peter John Bell, Philip Gordon Binns, Charles Russell Chrisp, Peter Hartley Coutts, Peter James Cross, John Perran Curry, William Ernest Digweed, Patrick Cornelious Alfred Donovan, Alan Sidney Henney, Maurice Donald Hodges, John Day Holland, George Charles Brian Harvey Kenrick, Eric David Marchant, Charles Frederick Matthews, John Osborn, Brian Henry Randall, Peter William Shaw, Guy Shepherdson, Thomas Smith, Alan Sydney Thurley, Albert William George Utting, Gerald Alfred White.

Companion

Jacqueline Borgel.

ADDITIONS TO LIBRARY

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

A.a.338—Introduction to Aerodynamic Compressibility. J. Black. Bunhill. 1947.

B.c.75—Helicopters of Tomorrow. B. J. Hurren. Staples. 1947.

B.f.101—Wing Tips: the Identification of Birds in Flight. Roland Green. Black. 1947.

B.g.155—The Aviation Annual of 1946. R. M. Cleveland and F. P. Graham. (Editors) Doubleday, New York. 1946.

L.d.116—*Notices to Airmen. Nos.* 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357.

*X.c.B.31—Authors' and Printers' Dictionary. F. Howard Collins. Oxford University Press. 1946.

A.R.C. Reports and Memoranda

2171—*Heat flow measurements. Ricardo & Co.*

2169—*The variation with air temperature of aircraft performance, engine power and temperature and fuel flow as determined by flight tests on a Lancaster I. W. J. D. Annand.*

2166—*A method of aerofoil design. Part I: Symmetrical aerofoils. B. Thwaites.*

2157—*The statistical estimation of the effect of size on the breaking stress of rods. C. Gurney.*

2155—*Ground resonance testing of aircraft. W. G. Molyneux and E. G. Broadbent.*

2150—*Reports and Memoranda published between 1st July 1946 and 31st December 1946.*

2113—*Note on the application of the linear perturbation theory to determine the effect of compressibility on the wind-tunnel constraint on a propeller. A. D. Young.*

2098—*Distribution of stress between spar flanges and stringers for a wing under distributed loading. D. Williams, R. D. Starkey and R. H. Taylor.*

2187—*An experimental technique for boundary layer research at high Reynolds numbers. A. V. Stephens and D. D. Craig.*

2158—*The effect of length on the strength of a steel wire. C. Gurney and S. Pearson.*

2125—*Sandwich construction and core materials. Part III. Instability of sandwich struts and beams. H. L. Cox, with appendix by J. R. Riddell.*

2160—*Measurements of pressure distribution on a Spitfire wing in flight at high speeds. W. J. Charnley and F/Lt. W. A. Mair.*

2071—*A simplified theory for streamline bodies of revolution, and its application to the development of high-speed low-drag shapes. A. D. Young and P. R. Owen.*

2059—*The calculation of aileron reversal speed. Mary Victory.*

2167—*A method of aerofoil design. Part II: Cambered aerofoils. B. Thwaites.*

2170—*Theoretical critical Mach numbers for N.A.C.A. 16 series aerofoils. E. J. Richards.*

2178—*The theory of flat panels buckled in compression. W. S. Hemp.*

2180—*Wind-tunnel tests on high-lift devices. H. M. Lyon and J. E. Adamson.*

2136—*Notes on the N.P.L. 13 ft. by 9 ft. and 9 ft. by 7 ft. wind tunnels. E. J. Richards and F. Cheers.*

2153—*Compression tests on dural-balsa sandwich panels. R. G. Chapman.*

2172—*Effect of various factors on heat flow in four-cycle petrol engines. H. R. Ricardo.*

N.A.C.A. Technical Memoranda

1160—*Concerning the velocity of evaporation of small droplets in a gas atmosphere. N. Fuchs.*

NOTICES

1157—*Cones in supersonic flow. D. Hautzsche and H. Wendt.*

1127—*Russian laminar flow airfoils. Third Part: Measurements on the profile No. 2315 bis with Ava-nose flap. F. Reigels.*

1167—*Calculations and experimental investigations on the feed power requirements of airplanes with boundary-layer control. W. Kruger.*

1183—*Temperatures and stresses on hollow blades for gas turbines. Erich Pollman.*

1187—*Equations for adiabatic but rotational steady gas flows without friction. Manfred Schafer.*

1190—*Tests of cascades of airfoils for retarded flow. Yoshinori Shimoyama.*

1184—*Development and construction of an interferometer for optical measurements of density fields. Th. Zobel.*

1179—*Determination of the stream concentration factor of a stepped shaft stressed in torsion by means of precision strain gauges. A. Weigand.*

1178—*Investigation of the operational properties of the leakage current anemometer. Wilhelm Pucke.*

1177—*Wind-tunnel investigation on a changed Mustang profile with nose flap force and pressure-distribution measurements. W. Kruger.*

1165—*Coefficient of friction, oil flow and heat balance of a full-journal bearing. P. I. Orloff.*

1138—*On the application of the energy method to stability problems. Karl Marguerre.*

1137—*The turbulent flow in diffusers of small divergence angle. G. A. Gourzhienko.*

The following reports have also been received:—

British Intelligence Objectives Sub-Committee

B.I.O.S. Final Reports No. 1494, Item No. 25; No. 1537, Item No. 9.

F.I.A.T. Final Report No. 626.

B.I.O.S./J.A.P./P.R./1485, 86, 89, 922, 826, 116, 894, 411, 1482 and 1465.

C.S.I.R. Division of Aeronautics

Reports SM 88 and SM 94.

Thornton Research Centre

Report No. R.192/47.0.

Politechnico di Torino

Reports Nos. 192, 193, 194, 195 and 196.

J. LAURENCE PRITCHARD,
Secretary.

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ACTIVITIES OF THE GRADUATES' AND STUDENTS' SECTION

January 1948

A programme of the Section's meetings for the first half of 1948 is published in this month's JOURNAL. Visitors are welcome at these meetings, and it is hoped that all members residing within the London area will endeavour to be present and bring a friend. Lectures are followed by a discussion in which any member of the audience is entitled to ask questions and to express his views.

During the summer months it is intended to arrange visits to aircraft firms and research establishments. Last year the Section visited the National Physical Laboratory, Teddington, the Miles Aircraft Co. Ltd., at Reading, and the de Havilland Aircraft Co. Ltd., at Hatfield Aerodrome. The latter visit was the first to take place on a weekday and, in consequence, was limited to the fortunate few who could take the day off. The visitors were rewarded with an interesting tour through the shops where they saw Doves and Hornets being built, and through the Vibration Department, Training School, and the engine test cells in which a Ghost turbine engine was being tested.

Members have already received notification of the new subscription rates which have been made necessary by rising costs. Subscriptions for Graduates and Students are based on a sliding scale according to age with no increase for students under 21 years of age, thus incorporating recommendations submitted by the Section committee.

LECTURE

On Wednesday, 19th November, 1947, Mr. John Yoxall, Art Editor of *Flight*, read a paper on "Aircraft Photography" before a meeting of the Section, held in the Council Room of the Society. Mr. J. W. F. Housego was in the chair.

Mr. Yoxall began by apologising because the talk he was going to give was mostly about himself, since it was an account of his own personal experiences in the field of aircraft photography. He had grown up with the Aircraft Industry, joining *Flight* 35 years ago, and had had nothing but excitement during that period, excitement tempered by an immense enthusiasm for his work.

He divided his talk into four parts. The first dealt with photographic apparatus and problems. His first camera was a 1912 Goerz half-plate camera with an f/4.8 Calor lens. With improved film emulsions, smaller sizes were adequate and this camera was replaced by a 12 × 9 cm. V.N. plate camera with an f/3.5 lens. More recently, films have been developed to such an extent that miniature film was used mostly now, and Mr. Yoxall's latest camera was a 35 mm. Contax with a 5 cm. f/1.5 lens.

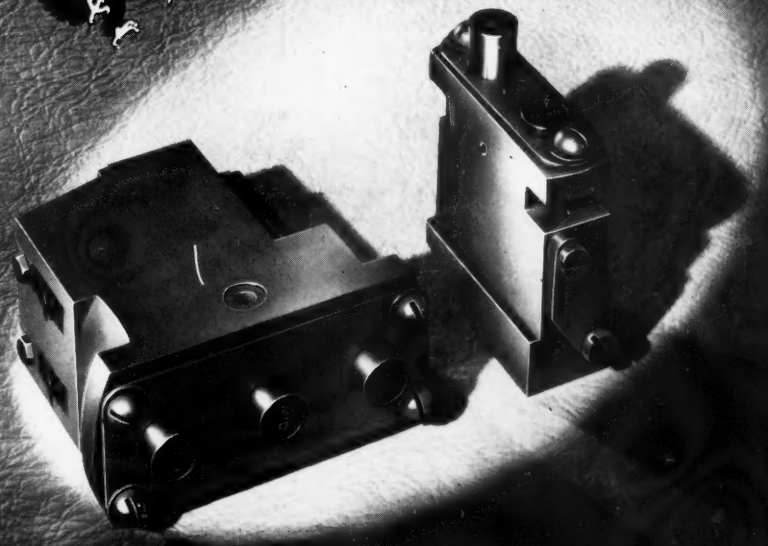
The second section was a description of the characteristics of a few of the 200 different types in which the speaker had flown. From the photographer's point of view, open cockpits were preferable to closed cabins, as movement was less restricted and the photographer did not have to contend with the optical disortion of windows.

The technique of obtaining successful photographs was outlined in the third part of the talk. This was illustrated by a number of slides showing examples of the attitudes in which aircraft were often photographed. The lecturer mentioned the hazards of standing without safety-straps or belts in a cockpit of a diving Skua, the danger of taking head-on photographs of an aircraft during take-off, and the accuracy of timing required when photographing a Spitfire from the rear turret of a bomber.

The final section was a selection of slides of good (and bad) photographs taken during Mr. Yoxall's 35 years in the profession. These covered such diverse subjects as infra-red photography through clouds and haze, including one of the earliest photographs showing the whole of London. Other photographs showed a Grebe fighter being released from the R.33 airship, and a "tied" formation of three Gauntlets. In showing the latter slide, the speaker expressed his fears (or hopes) that this feat would one day be performed with Vampires.

The meeting was then opened to discussion, and Mr. Yoxall answered a number of questions, many of which dealt with the subject of photography in general.

MESSIER



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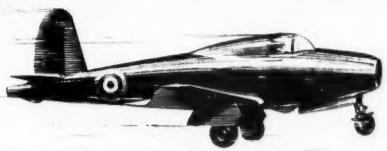
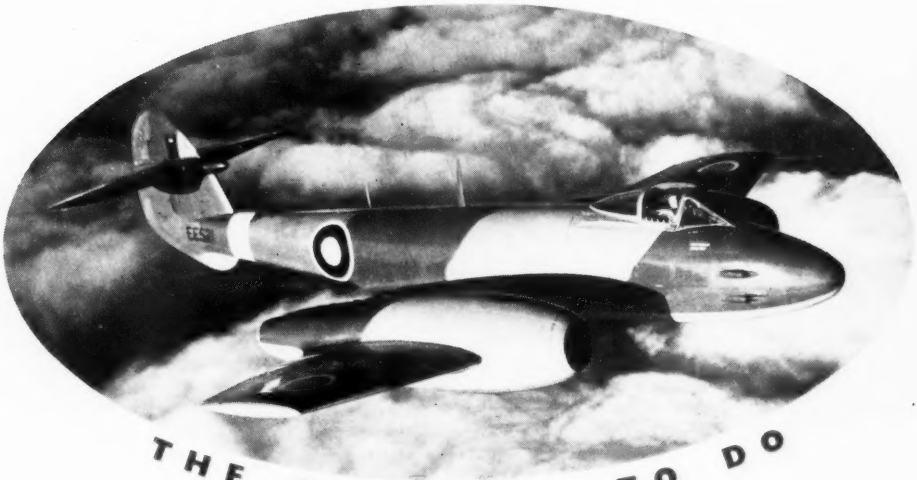
THE COURAGE TO THINK





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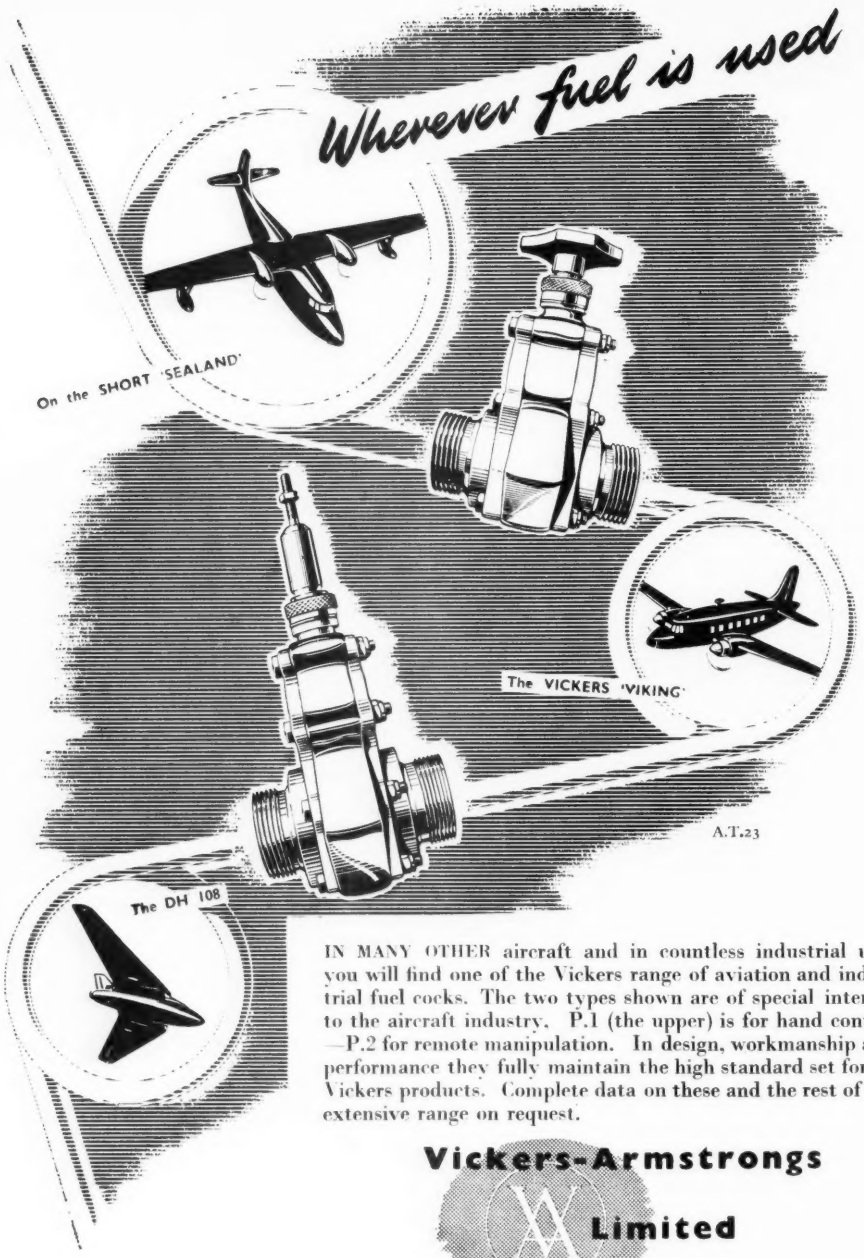

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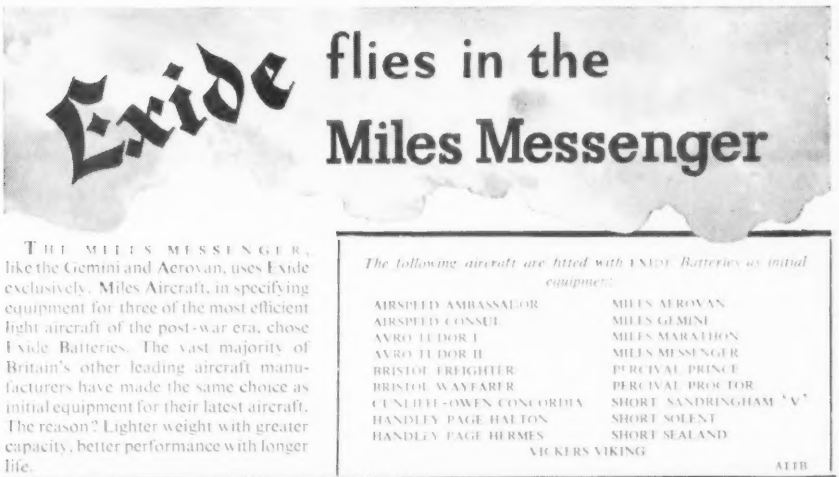
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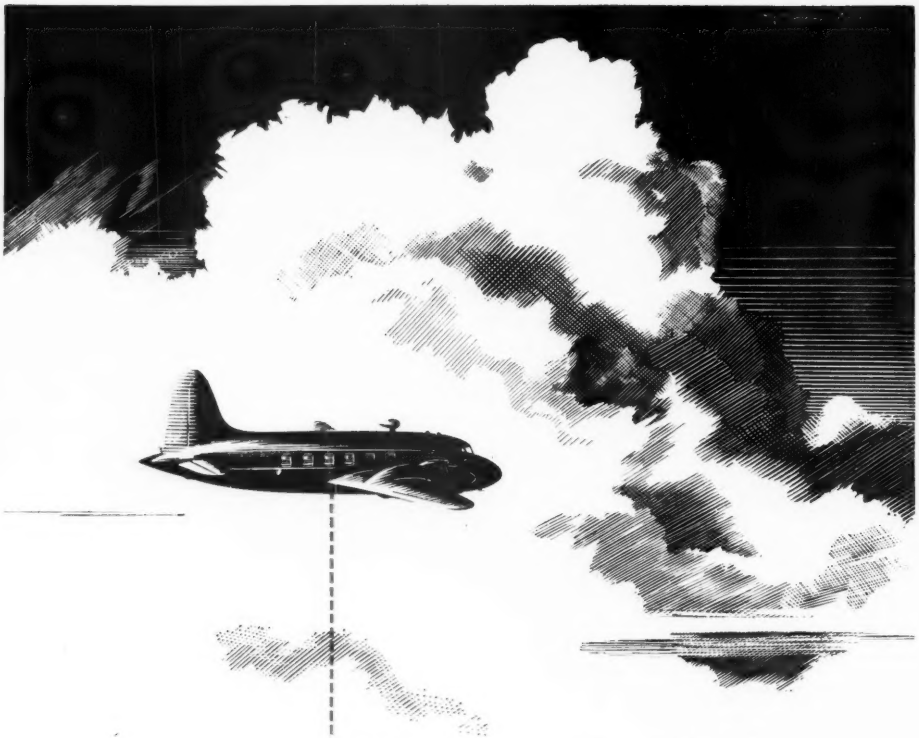

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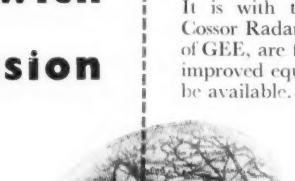

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The 739th Lecture read before the Society—on 23rd October 1947 at the Institution of Civil Engineers, Great George Street, London, S.W.1. In the Chair, the President, Dr. H. Roxbee Cox, D.I.C., F.R.Ae.S.

THE PROBLEM OF HIGH TEMPERATURE ALLOYS FOR GAS TURBINES

by

Sir WILLIAM T. GRIFFITHS, D.Sc., F.R.I.C., F.Inst.P., F.I.M.

Sir William Griffiths obtained his doctor's degree at the University of Wales, Cardiff. After serving during the 1914-18 *War he was research metallurgist at Woolwich Arsenal for five years. In* 1926 *he joined The Mond Nickel Company Ltd. as manager of the research and development department. Since* 1945 *he has been Chairman and Managing Director of The Mond Nickel Company and Vice-President of The International Nickel Company. He was recently appointed a member of the Government's Advisory Council on Scientific and Industrial Research. He is a Past-President of the Institute of Metals.*

IT is now a matter of history that the development of an efficient gas turbine for use in aircraft engines had to await the availability of materials with the properties which would give an adequate life under the conditions which have to be imposed for efficient and economic service. These conditions are, of their type, more severe than any so far imposed on materials in other mechanical equipment. For efficient operation the gases employed in the turbine must be at a high temperature and the flow of gas passing through must be large. In aircraft engines also, the turbine must operate at high speed, with the resulting accompaniment of high stresses. It was to the metallurgist that the engineer naturally turned first for materials to meet these conditions of high temperatures and high stresses and, although some attention has been given to non-metallic substances, the problem still remains essentially a metallurgical one.

At the beginning of the late war, although alloys had been devised which were a great advance on any previously produced, the properties possessed by them were still not quite adequate to the task. The enormous possibilities for the military use of aircraft powered by jet propulsion units, stimulated early in the war an intensified effort in this country, and elsewhere, to devise alloys better able to meet the service conditions. The results of these researches were such as not only to make possible the jet-propelled aircraft of the late war period, but also, to make it likely that the engines of all aircraft in the not-too-distant future will incorporate a gas turbine, either as part of a jet reaction engine or for driving a propeller.

The success of the past few years has not been attained without close co-operation between engineers and metallurgists, but progress has not been without its interruptions consequent on an occasional insufficient appreciation, on the part of one or other of the collaborators, of the problems involved. Now that the gas turbine is attracting a wider interest than was possible under war conditions, it was thought that it might be helpful once again to review the considerations involved in the problem of providing adequate high temperature materials. They have been referred to more or less generally in a number of papers published in the past two years, but it is hoped that a general review at the present time, even if containing little that is new, will at least be stimulating of thought and perhaps, discussion.

Four main parts of the gas turbine operate at high temperature. These are:—

(1) The rotor blades.
(2) The rotor disc.
(3) The nozzle guide vanes, and
(4) The combustion chambers and discharge arms.

Each part has its own particular metallurgical problems.

1. ROTOR BLADE MATERIALS.

It has been in the provision of a material for the moving blades that the greatest metallurgical problems have been met with, since here the most severe combination of stress and temperature is imposed on a part which design requires to have exactness of dimension in a quite complicated shape. The various requirements may be discussed separately.

(a) Mechanical properties in the cold.

In order that any material can be used for blades, it must clearly have such mechanical characteristics as will allow it to be fabricated into blades and for these blades to be built into the wheel assembly without too great difficulty. It must also be able to withstand the stresses imposed during starting up from cold.

As in most component material problems, a combination of properties is required. Obviously, the advantages of high strength and hardness may be counterbalanced by the necessity of grinding in shaping the blade and its root section, or by the existence of excessive brittleness, increasing risk of breakages during assembly or from the accidental imposition of shock.

With the present designs and requirements it is not too difficult a problem to provide an alloy with reasonably adequate properties in the cold. If service temperatures rise considerably, and more complex alloys, or even non-metallic materials have to be used, the possible accompanying extreme hardness or fragility in the cold will have to be taken into account. It has to be remembered, too, that although a material may have satisfactory properties in the cold when first put into service, exposure to high temperatures may facilitate changes which, even while not affecting life at temperature, may introduce dangerous brittleness or fragility in the cold.

(b) Creep resistance.

It has long been known to engineers and metallurgists alike that a consideration of tensile properties at elevated temperatures differs from one of these in the cold in that, in the case of the majority of engineering materials, the time factor is of so much more importance at high temperatures. Except in the case of a few alloys, such as those of lead and tin, it is possible to assume that for most metallic materials a stress can be determined below which fracture will not take place at room temperature, however long it is applied.

At high temperatures the position is different. For any given metal or alloy there is a temperature above which it is not possible to state with certainty that fracture will not take place under any given stress, if that stress is left on long enough. The quick break test of the ordinary laboratory tensile machine, even if made at the service temperature, gives no indication of the stress below which the alloy will not fracture in service.

In considering the behaviour of materials under so-called "creep" conditions—and it is in these conditions that blade materials are performing in a gas turbine—it is of great importance to remember that many of the deductions commonly made by engineers from the simple tensile test, when designing for service in the cold, cannot be made from a single creep test, considered by some the corresponding high temperature test. The question is worth studying further.

The normal creep curve (Fig. 1) is one in

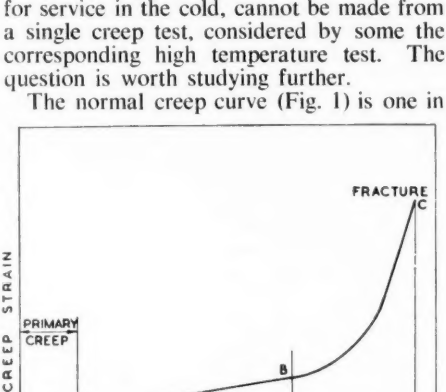

Fig. 1.
The creep curve.

which "strain" is plotted against "time," and the single curve shows the progressive extension of the test piece when a given stress is maintained at a given temperature. The strain ordinate usually plotted is that which occurs over and above the elastic strain. The stress/strain diagram is generally plotted while loading up the test piece, and strain deviations from the proportional line are regarded as "creep strains" and are plotted as such.

In general, a creep curve may be divided into three parts representing:

(i) The primary creep stage, when relatively rapid extension takes place, but at a decreasing rate.

(ii) The secondary period during which creep occurs at a more or less constant rate, sometimes referred to as the minimum creep rate.

(iii) The tertiary creep stage when the rate of extension accelerates and finally leads to rupture.

It is perhaps not unfair to say that, although there are theories in existence, the exact significance of these three stages and what they portend in inter-atomic movement and in adjustments of the granular complex, of which all metallic substances are composed, is still uncertain. It has been one of the great difficulties of the metallurgist in developing alloys for service under which creep is taking place, that he can yet only guess as to the nature of "creep." Further progress should be easier when there become available the results of researches on the fundamentals of the phenomenon which, it is understood, are under way. The advances up to the present have had to be made in a somewhat groping empirical way, a method apt to be time-absorbing and with many a disappointment for every small step forward.

The primary stage (OA) of the curve is mainly of interest to the designer for the part it forms of the total extension reached in any given time. Since clearances between blade tip and stator have to be kept to a minimum, the smaller AM is the better.*

Our knowledge is perhaps least concerning what happens during the tertiary stage. Obviously, rapid and fundamental changes are in progress. One theory holds that the accelerated extension in this stage is caused by, or at least accompanied by, the development of minute inter-granular cracks. Whatever be the exact significance of this tertiary stage it would seem preferable that, in the present stage of knowledge, materials being used under conditions involving creep should not be allowed to enter this stage. And, it should be noted, the control in this connection is absolute, since the horizontal ordinate is *time*. For this reason the service life of any component subject to creep should be limited to a period which in length does not approach ON.

It follows that one of the most important pieces of information which one requires from a creep curve is the time (ON) to the point B, and this should be known as accurately as possible for the maximum design stress. It would seem advisable, if the maximum safe life is wanted from the material, to keep a record of the time at full throttle, when the blade is subjected to the severest combination of stress and temperature. The alternative to keeping such a record is to make the time "factor of safety" larger.

"Life" should date from the time when the blade is first exposed under stress to the highest temperature. One has heard suggestions that if a blade should extend under creep so that clearance disappears, it might be trimmed to original size and service continued. This may be done if necessity demands, provided that the reason for the excessive extension is known and it is certain that it is not due to stress or temperature having exceeded those designed for by a large margin. It is certainly not advisable however and, if it has to be done, it must be remembered that the blade is not new and its further service must not exceed—preferably it should be much less than—the remaining portion of the life originally planned.

The point B is sometimes not easy to determine on the creep curves for some materials at certain stresses and temperatures. The slope of the creep curve may change almost continuously. In the present state of our knowledge all that can be done in such cases would seem to be to leave an ample "factor of safety" in deciding on the allowable service life from a knowledge of the time when the rate of extension is definitely accelerating.

If it is accepted that service life should never approach ON in length, it is reasonable to query whether any importance should be attached to a determination of OP or PC, the "time to fracture" and the "extension at fracture." The question is of importance because the former has frequently been used to compare the qualities of different materials and the latter has been taken to be a measure of what has been called by some "ductility."

It is clear that the shape of the curve BC must be determined in order to ascertain the position of the point B. To try to draw deductions from the figures for OP and PC, however, seems to indicate some confusion in thought between the strain-time "creep curve" determined for one stress and one (elevated) temperature and the common stress-strain curve determined, generally at room temperature, in the quick break tensile

*See p. 10.

machine. Long experience of relating the indications of the stress-strain curve with behaviour in service, has enabled engineers to deduce from the curve the quality of a material and its suitability for a given type of service. Even this curve however is of use not so much because of the knowledge it gives of the stress at which fracture takes place, but because of the deductions which can be made of what will happen under other, lower, stresses.

The most important part of the creep curve is undoubtedly that which lies between A and B. The slope of this portion and its length are indications of the quality of a material for service at the particular temperature and stress, the best material clearly being one with a uniform low rate of extension continuing over a long period. Even this part of the curve gives no indication of the ability of the material to withstand the effects of other stresses and temperatures, and it is the possible fortuitous increase of these that give the designer most cause for concern.

The limited nature of the information available from any one creep curve becomes clearer when a series of curves is considered. In Fig. 2 is given a family of curves for one material obtained by loading separate specimens with various stresses at the same temperature and, in Fig. 3, are given other curves in which the stress has remained constant and the temperature of test has been varied.

It will be noted that as the applied stress decreases, the primary creep stage decreases, the secondary stage is extended and the minimum creep rate (the slope of the curve in the secondary stage) is reduced. It will also be seen that as the duration of the secondary stage increases, the extension during the tertiary stage tends to decrease. This appears to apply in the case of all metallic materials tested under creep conditions, although obviously the stress producing a given extension during the secondary or tertiary stages varies considerably from alloy to alloy. In general the extension during tertiary stage does not fall

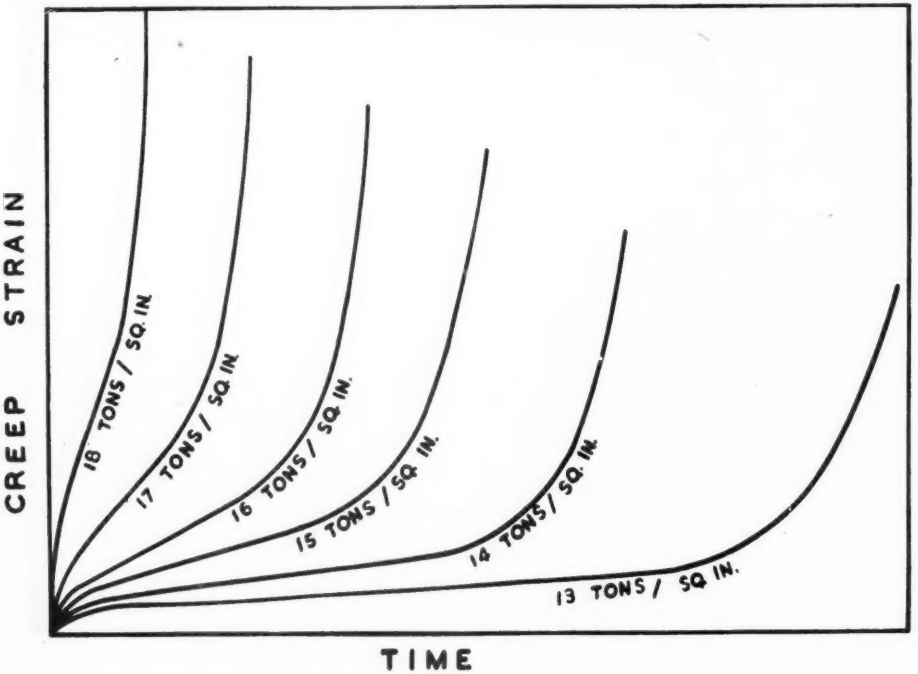

Fig. 2.
Creep curves for one material under various stresses at one temperature.

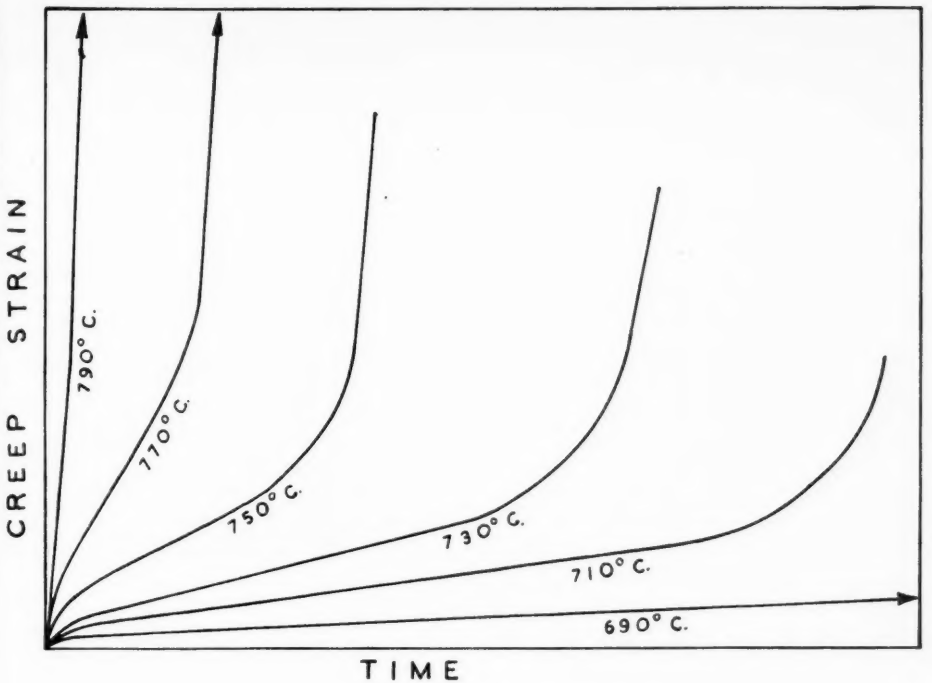

Fig. 3.
Creep curves for one material at various temperatures under the same stress.

below a minimum characteristic of the material, however much the duration of the second stage is extended by lowering the stress.

Modifying the temperature of test has a similar effect on the shape of the curves. It will be appreciated that the effect of a relatively small increase of temperature may be considerable, particularly when a material is approaching the maximum reasonable service temperature for a given stress.

It will be obvious why "time-to-fracture" on one curve, in the absence of other curves, can give no very exact indication of the likely behaviour at other stresses or temperatures and why the comparison of two materials on the basis of "time-to-fracture" at one temperature and stress may be quite misleading.

Figures 2 and 3 also show why the extension at fracture on one particular curve cannot be taken as a measure of "ductility" exhibited in service. If at the start of a blade's life, for example, the stress at any point of the blade is raised by a stress raiser, caused perhaps by faulty machining or fitting, the material at that point will not follow the strain-time relationship of the curve for the designed service stress. It will immediately follow one of the upper curves on Fig. 2. Similarly, local over-heating will change the relationship. Relatively rapid local creep will, of course, be accompanied by stress relaxation and tend to bring the relationship back to the lower curve.

Again, supposing that there should be a fortuitous increase in stress or temperature after the blade life has proceeded to the stage represented by the point X on the creep curve OABC (Fig. 4) the strain-time relationship will no longer follow the line XBC. If the increase of stress or temperature is appreciable, a curve such as XF may be followed. If there is a smaller increase, a curve somewhat like XG might well be traced. Exactly what will be the shape of these curves will depend on the previous history of the high temperature exposure and other factors. It will be clear from Figs. 2 and 3, however, that the elongation at fracture is likely to be greater, perhaps

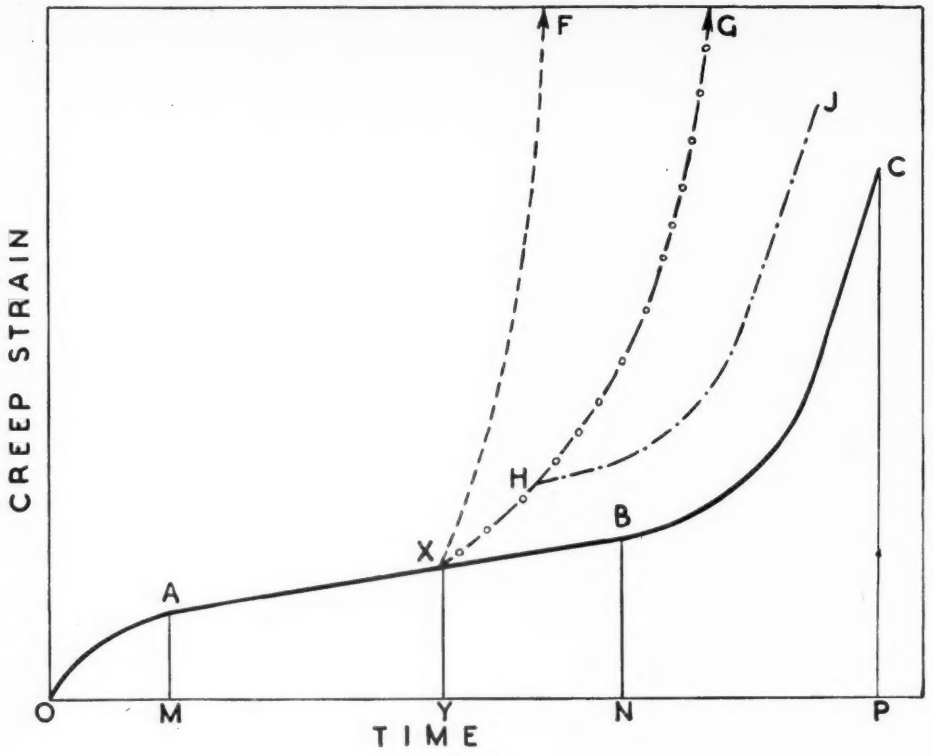

Fig. 4.
Effect of sudden change of stress or temperature.

considerably so, than the amount shown by CP on the original curve.

Fig. 5.

If at the situation represented by the point H the added stress or rise of temperature is removed, a curve such as HJ may well be followed.

The above considerations are illustrated by the blades shown in Fig. 5. These were made from an alloy which is said by some to show low "ductility" because, after a long continued creep test it gives a rather small "extension-at-fracture," compared with some other materials. The blades were two of several which, after some time at temperature in a turbine, were subjected to an accidental considerable increase in stress. As will be seen, the blade did not break but exhibited as ductile a behaviour as could be desired.

Figure 6 shows part of a rotor assembly which carried blades in the same material and operated in an engine deliberately over-run.* After 30 minutes of over-running the

*The author is indebted to Dr. H. Roxbee Cox, Director of the National Gas Turbine Establishment, for permission to refer to this test.

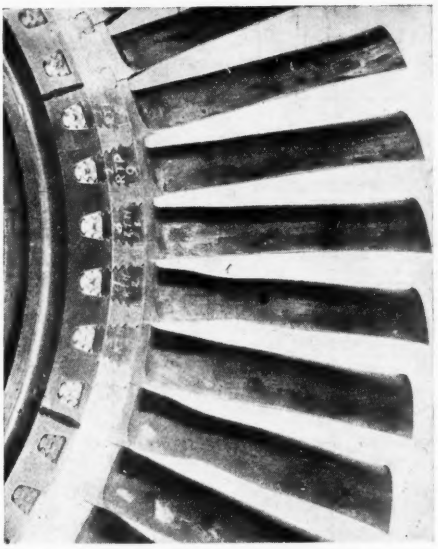

Fig. 6.

blades showed substantial elongation (some as much as 30 or 40 per cent.) in the critical region towards the blade root. In no case was any sign of cracking to be observed. This extreme elongation had been accommodated by the tips rubbing away without galling the surrounding ring.

Figures 2 and 3 are for one material. They may be very different for another alloy, not only in the shape of an individual curve for a given temperature and stress, but also in the separation of the curves caused by variation of temperature or stress. This has to be recognised definitely by engineer and metallurgist alike, for it means that it is not possible to determine the likely behaviour of an alloy at one temperature and stress by making a test at some other temperature or stress. For example, testing time cannot be shortened usefully by raising stress or temperature, except perhaps in the special case mentioned below.

It also means that a comparison of two materials can only be made properly by tests done at the temperature to be used in service. There has been a not inconsiderable and widespread tendency to argue that if one material is better than another at one temperature, it must also be better at some other, generally lower, temperature. This is frequently not the case, the alloy giving the best test figures at, say, 800°C. being relatively the poorer at temperatures of, say, 700° or 650°C.*

For the reasons given above it is necessary, in judging the quality of an alloy or designing for its use, to have creep data for it over a range of temperatures and stresses. These data are usually assembled in charts of the type illustrated in Fig. 7.

It will be appreciated that the collection of the data for such a diagram is a lengthy procedure, requiring the making of a large number of complete creep curves at a variety of stresses and temperatures. Fortunately, for a variety of reasons, aircraft power units are not expected to have lives at "full throttle" exceeding some 300 hours.† Even so, the obtaining of the data required must obviously involve the use of large numbers of the complicated and expensive creep machines, which require relatively skilled staff to operate them. This is no small part of the problem of providing ever better high temperature alloys.

Because of the time involved in the full creep test there have been many suggestions made for the use of shorter time tests.[1] Such tests have their value when the data are interpreted by those experienced in high temperature materials research for the preliminary comparison of a variety of closely similar compositions, or of the effects of different treatments on one composition. They can only be used with caution and no alloy should be chosen for service on the basis of evidence other than that obtained from complete creep curves.

The question of creep has been dealt with in some detail, since creep phenomena distinguish so markedly the behaviour of materials at elevated temperatures from that at ordinary temperatures. It is vitally important that engineers and metallurgists should both think along similar lines and should have a uniform interpretation of creep curves as drawn. From the discussion too, it is hoped that it will be appreciated how slow the development of a new creep-resisting alloy may well be and what a considerable amount of laboratory work is called for, before even experimental plant production can be initiated justifiably.

*The stresses which both will withstand at the lower temperature are, of course, higher than those borne safely at the higher temperature.

†This, of course, means service life of at least 1,000 hours, equivalent to a mileage certainly exceeding a quarter of a million.

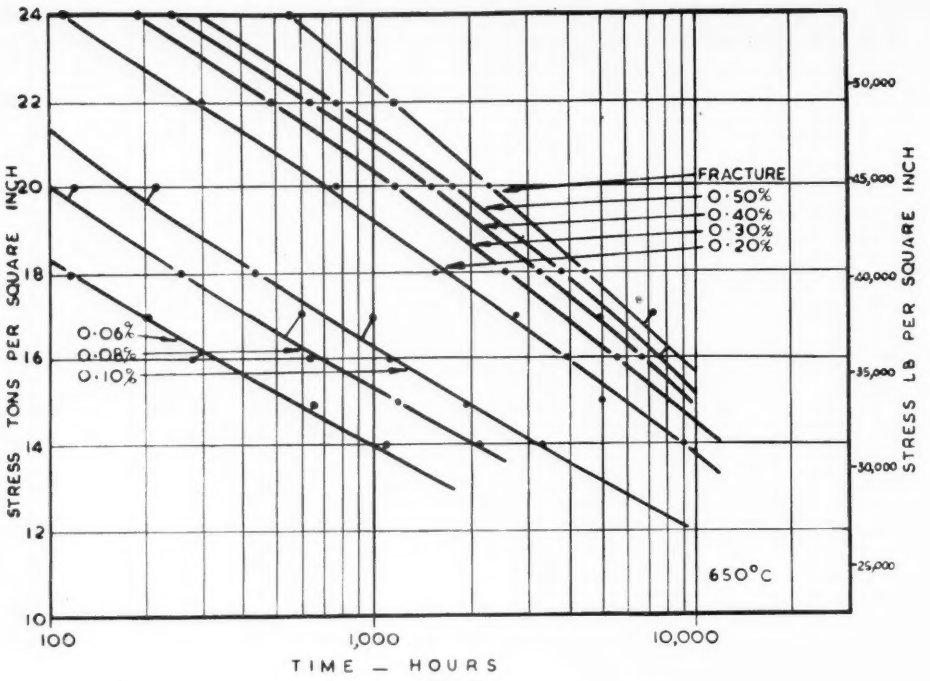

Fig. 7.
Design data at one temperature (650° for the alloy "Nimonic 80").

(*c*) *Fatigue resistance at high temperature.*

Rotor blades are not subject to tensile stress only. They have imposed upon them also, the gas bending stress and this may vary as the blades pass the nozzle guide vanes. A satisfactory blade material, therefore, must be able to withstand the effects of the combined creep and fatigue stresses.

Our knowledge of the effect of fluctuating stresses on a specimen which is extending under creep is as yet extremely limited. Some work has been done with the aid of Wöhler-type machines, but these are far from reproducing the conditions under which a blade operates, since a zero mean stress alone can be imposed and it is doubtful whether deductions from such data can be applied to a case where the mean stress is high and is itself causing plastic deformation.

Haigh-type machines have been specially adapted in recent years to permit high temperature fatigue tests with high tensile mean stresses, and some data have thus been accumulated. But as the imposed fluctuation in these machines is not of a bending stress, there is still an element of doubt in drawing deductions from the figures obtained as to the service life of a material in a turbine blade.

Another complicating factor is that the blades in an aero-engine gas turbine are vibrating at a frequency which is much higher than any that, so far, has been reproducible in the Haigh machine, and little knowledge exists as to the significance which should be attached to the frequency factor.

There is undoubtedly a considerable need for a machine which will more accurately reproduce service conditions and, until that is available, the metallurgist endeavouring to devise improved blade materials has little to guide him in this direction. The question appears to be an important one, since it is clear that stresses which may cause failure by fatigue exist and some blade failures seem to have a characteristic "fatigue fracture."

This particular aspect of the subject is also difficult at the moment, since it has not proved possible so far to estimate with any accuracy the range of the stress fluctuations

to which turbine blades are, in fact, subjected. More accurate information in this direction would be extremely helpful.

The possibility of fatigue failure adds emphasis to the advisability of limiting the service life of blades so that there is no possibility of creep entering the tertiary stage, particularly if there is any likelihood that this stage is accompanied by the development of internal discontinuities. Any cracks formed would naturally produce concentrations of stress and notch effects which might be serious where fluctuating stresses exist.

The necessity for resistance to fatigue has naturally raised the question of "damping capacity," and there was at one time a tendency to search for materials in which the inherent damping capacity was high.

It has been pointed out that if blades are attached to the rotor by a fir-tree, or similar type of attachment, the mechanical damping that is produced is such that the damping capacity of the blade material is of relatively small importance. If the blades are welded to the rotor, the situation is different since then the mechanical damping might be quite small.

Such investigation as has been made into the damping capacity of materials which might be used for blades, appears to indicate that where a high temperature material is used under stress and temperature conditions, such that it offers the required high resistance to creep, the damping capacity is low. This has to be accepted in considering blade sections and method of attachment to the rotor.

(*d*) *Oxidation and corrosion resistance.*

Since turbine blades have to operate in contact with hot gases, the material of which they are composed must have adequate resistance to the corrosive attack of those gases at the temperature of operation. Apart from the noble metals—and these could hardly be used for major turbine parts—all heat-resisting alloys in common use depend for their oxidation resistance on the development of a protective oxide film. Two metals are of outstanding importance in facilitating the formation of protective films, chromium and aluminium. Of these two, chromium has been by far the more important in the materials so far developed.

In order that chromium should be effective, at least 10 per cent. must be present in the alloy and resistance generally improves as the chromium content rises. If much more than 20 per cent is present production difficulties tend to increase, particularly in regard to the "cleanliness" of the alloy and the ease of fabrication.

Aluminium is perhaps more potent than chromium in providing a protective film, but at quite low contents the difficulty of forging, and so on, becomes crippling.

Nickel has proved a useful constituent of oxidation resistant alloys, withstanding oxide formation itself and assisting in providing a structure helpful in avoiding attack.

At the temperatures at which turbine blades have so far been asked to operate—say, 750°C. or less—many materials are available which, generally because of their chromium content, have quite adequate oxidation resistance. Should temperatures go higher, this problem may require further attention.

The oxides of some metals are volatile. When this is the case, protective films are obviously only formed with difficulty, there is a loss of the particular metal from the surface of the blade, and a danger may exist of the formation of surface irregularities providing notch effects.

Resistance to certain types of corrosion may be of importance because of the corrosive effect of some fuels, or their combustion products. In some military aircraft engines, for example, the possibility had to be envisaged of having on occasion to use the doped fuel employed for the reciprocating types of engine, and this raised the question of the resistance of the blade materials to attack by the lead and other constituents present in these fuels. In this particular case the nickel-chromium alloys are outstanding, having been employed for some time in reciprocating engines for the protective coating or covering of the valve heads.

(*e*) *Stability.*

Since rise of temperature favours change of metallurgical structure, it is important that alloys employed in blades should not undergo change to a dangerous extent during their exposure to service temperatures. As is no doubt known, the majority of alloys which have so far been suggested for blade materials develop their high temperature strength after a heat treatment which involves first, the solution and then the partial "precipitation," of one or more solutes. It would seem preferable for an alloy of this

type that at the temperature at which it is to be used, further change does not proceed, or only proceeds quite slowly. In developing a new alloy, therefore, this possibility has to be examined by making long-time tests and determining, generally by physical means, whether any change takes place and how it proceeds. It should be noted that the presence of strain may expedite structural change.

Mention may be made here of creep curves which seem to indicate that an alloy does not creep for some time after the application of stress at temperature; indeed, on occasion reference has been made to "negative creep," there being initially a contraction of the alloy. It has to be remembered that such lack of creep, or negative creep, is probably caused by a continuance of structural change in the alloy itself, this being accompanied by a dimensional contraction. The extension caused by creep is thus masked. It might be queried as to whether it is advisable to put an alloy into service in this unstable condition.*

(*f*) *Physical properties.*

Physical properties such as co-efficient of thermal expansion, specific gravity, and so on, are necessarily of importance. A low co-efficient of expansion allows smaller clearances to be left, and minimises risk of distortion at times when temperature gradients exist, as during starting. The lower the specific gravity of a blade material the better, since the main stress is centrifugal.

(*g*) *Ease of fabrication.*

The present-day gas turbine blade has a complicated section with small radius edges, and accuracy of dimension is of importance. The blade root, too, has to be shaped so as to fit into the disc recesses. Any useful blade material therefore must lend itself to being given the required shape.

(i) *Forgeability.* The requirement of forgeability is not easily attained in a material which is expected to have strength at high temperatures. Forging temperatures, therefore, must be higher than service temperatures and they must also not approach too closely to the melting point of the alloy. The problem has been partly solved by the use of heat-treatable alloys which, although stiff at forging temperatures, are soft enough to be workable with care. Following forging, they are given a heat treatment which, generally by partly precipitating a constituent in solution at the forging temperature, increases considerably the strength at the service temperature.

It has to be recognised that, as service temperatures are required to rise, the difficulty of providing a forgeable alloy must increase.

(ii) *Castability.* "Castability" is of importance when an alloy cannot be forged, because it is too hard or too brittle to fabricate when solid. Developments of the "lost wax" casting process have attracted attention to the possibility of producing castings in this type of alloy which will have sufficient precision to be used "as cast," or with little further work. Some alloys are said to be more easily castable by this process, although the comparative data which has been published is not sufficient to be conclusive.

The structure of the alloy in the cast condition is of considerable importance. Not only does this affect the creep strength, but it can in certain circumstances reduce the resistance to fatigue, particularly of thin blade sections subject to fluctuating bending stresses. Resistance to shock also tends to be lower in a cast alloy, especially if the impact is in the direction in which the principal axes of the crystals lie.

Castings, it is well known, are more subject to property scatter than wrought material and great care is necessary therefore in controlling conditions during production, while ample "factors of safety" are best allowed.

(iii) *Machinability.* Ease of machinability is obviously helpful in producing a blade to exact dimensions. There are also advantages, as has been proved in steam turbine practice, in removing from the surface of a blade any portion of the material which has been excessively distorted during the forging operation, or which may have become contaminated or attacked during casting or heat treatment. Although, clearly, in order to be machinable, an alloy must not be too hard, excessive softness produced in certain ways can result in "tearing" and surface imperfection. For each alloy, therefore, particularly those subject to heat treatment, the best condition for machinability has to be determined.

Alloys which owe their strength at high temperatures to their complexity are frequently extremely hard at room temperature,

*This should be noted in connection with the paragraph on p. 3 about the creep curve.

and their machinability a matter of difficulty. Grinding can be used, but may be an expensive form of shaping.

(iv) *Weldability.* If it is intended to attach the blade to the rotor by welding, the welding characteristics of the alloy become of importance. Here the effect of minute quantities of some elements can often be pronounced. On the other hand, it may be difficult to avoid the use of such elements either to produce the high temperature strength, or to assist in the production of sound, workable material.

(*v*) *Heat treatment requirements.* Clearly, elaborate heat treatments do not assist ease and rapidity of fabrication. Many alloys depend upon the carrying out of at least two heat treatments—a long time soaking at a temperature above 1,000°C., followed by heating for several hours at some lower temperature. The optimum conditions have necessarily to be determined for each alloy. When this has been done the procedure should be followed exactly; economies by shortening heat treatment times, or by using some convenient, but too fast or too slow cooling rate, may well have a marked effect on the high temperature properties obtained.

Heat treatments which involve soaking at high temperatures are naturally expensive and, as has been indicated above, require a high accuracy of control if the temperature is near to the melting point of any constituent in the alloy.

(*h*) *Availability of component elements.*

It seems likely that high temperature alloys will always tend to be complicated in composition, and many already contain a variety of elements not previously used to any great extent for the common engineering alloys. Before any alloy is chosen there must necessarily be some assurance that a supply of all the constituent elements will be available in the necessary quantities. The problem is not too difficult in time of peace, but may become of major importance in time of war.

(*i*) *Regularity of properties in quantity production.*

It need hardly be emphasised that the problem of meeting the engineer's requirements for a rotor blade material is only partly solved by the development in the research laboratory of a composition which, when made and treated under laboratory conditions, will have the various desired qualities. An alloy can only be specified as an engine component when it can be made available regularly in large quantities, always possessing in the completed component the required characteristics. The solving of this part of the problem has been a metallurgical achievement of a magnitude not perhaps generally realised.

High temperature properties, and particularly creep resistance, are sensitive to quite minute variations in composition, processing and treatment. The presence or absence of 0.001 per cent. of one constituent, or a change of 0.1 per cent. in the content of another, may make the difference between a completely satisfactory alloy and one which would fall short of specified requirements.

Many of the alloys proposed for blade material have, apparently necessarily, complicated compositions, there sometimes being as many as ten elements essentially present. These alloys have to be compounded from a number of addition alloys or mixtures, each of which may bring in impurities. Further contamination is possible from furnace or ladle linings, the atmosphere in which melting and pouring proceeds, and the "de-oxidants" with which the melt has to be treated. Control of all these factors therefore has to be strictly maintained. This type of control is not uncommon, of course, in the melting of high quality alloys, but, at least with the knowledge available at present, the degree of care called for in the case of high temperature materials is certainly greater than that with other alloys.

A procedure for using up scrap has also to be developed. With high quality alloys used for accurately dimensioned components, the scrap produced can be a high percentage of the ingot weight cast. On the other hand, scrap can be used only with the utmost caution, high temperature properties being seriously affected if the scrap should be contaminated, or if the melting procedure is not suitably modified when scrap is added to the bath.

Then, most of these alloys seem to possess freezing characteristics which make the obtaining of a sound ingot free from centre weakness quite difficult. Ingot moulds of special size and shape have, therefore, to be used.

The intrinsic difficulties of working these alloys of high temperature strength has already been referred to and they can only be reduced to the bar required for blade forging

or machining, by the most meticulous care in forging and rolling operations. The production of the minutest of internal cracks in the billet or bar may completely vitiate any high temperature quality. Even slight overheating may be fatal, while the properties of some alloys are spoilt if they are worked at too low a temperature.

Another problem which has had to be solved has been in meeting requirements which have been specified for "cleanliness" in the finished blade forging. Most of the promising compositions contain one or more of elements such as chromium, niobium, aluminium, titanium, and so on, which readily combine with oxygen or nitrogen, often producing insoluble compounds which, if not completely removed during the pouring and solidifying stages remain distributed throughout the solid metal. The presence of any such inclusion visible on a polished surface, either to the naked eye or under a low-powered microscope, has up to the present resulted in the rejection of the finished blade. Such rejection has perhaps been justified while engine development is in progress and until more is known as to the reasons for blade failure, but it must be recognised that the maintenance of such a standard is bound to affect cost.

The susceptibility of high temperature properties to the effects of these numerous factors, separate and combined, perhaps explains why so frequently during the past five years one has heard of alloys with "remarkable properties" which somehow have never become available in commercial quantities. The manufacture of such materials as have been provided in sufficient amount has only become possible by a detailed examination of the effect of each of the variables, not only by laboratory experiment but by the making of works' heats and the reduction of the works' produced ingots. This has naturally meant the determination of very large numbers of creep curves, mostly of 100-hour or longer duration, since not only does a change in one variable frequently affect the potency of another, but such changes may require a modification of the heat treatment necessary to produce optimum properties.

Even to-day when creep resistant materials have been made in quantity for some time, it would be rash to claim that a complete understanding of the effect of every variable is accurately known, and at least one manufacturer considers it necessary to make one or more creep tests on every heat of alloy before deciding whether the batch should be released for sale.

Such "routine" check creep tests on an alloy composition of which considerable experience has been acquired, need not be carried to fracture. They must, however, be of sufficient duration to demonstrate that the curve is following the normal shape, that the minimum creep rate (the slope of the secondary stage) does not exceed a given maximum, and that tertiary creep is not initiated within a given minimum time. For this reason large numbers of creep machines must be given up to such check testing, although these machines can clearly be of simpler design and operation than those required for research purposes. This routine testing, made on an alloy of which the characteristics are well known, is perhaps the only case where testing time can be reduced by an increase of stress or a slight raising of the temperature. Even then before relying on any such shorter time test, its indications must be correlated with those of the normal full-time creep curve.

It will be seen that the development of a satisfactory rotor blade material is a matter of some complexity, calling for much painstaking investigation, both in the laboratory and in the works. Advance must necessarily tend to be slow if the result of the metallurgist's labour is to be accepted with confidence for design purposes. The more precise the engineer can be as to his next requirement, the greater is the chance that he will get it quickly. The use of such phrases as, "the sky's the limit," tends simply to limit the speed at which the unit requiring an improved alloy will get into the sky.

2. THE ROTOR DISC.

The problems connected with the development of a satisfactory rotor material are somewhat similar to those met in providing a suitable blade material. The emphasis on the various requirements differs somewhat, however, and disc materials have their own special difficulties.

The operating temperature of the rotor or disc in an aircraft gas turbine is clearly lower at the centre, than at the rim, and the temperature of the rim is somewhat lower than that of the inset blades.

As a result of the radial temperature differences, stresses arising from the thermal

expansion of the material are superimposed on those arising from the high speed of rotation. The most severe stresses occur at the centre of the disc and accordingly, attention must be paid to the mechanical properties, such as yield point, tensile strength, and so on, which are normally significant in metallic materials required to operate near room temperature.

The stresses arising from temperature differences in the rotor will naturally depend on the thermal conductivity and co-efficient of expansion of the material, so that these factors are of particular importance in selecting a disc material. Scale resistance is naturally less important in a rotor than in some of the other gas turbine parts, but this property cannot be ignored because rim temperatures may well exceed 600°C., at which temperature scaling may proceed at an appreciable rate, except in the case of materials falling into the heat-resisting class.

Stresses in the hot rim of the disc reach levels where creep may occur and it is essential to make use of a material which has a satisfactory creep resistance at the rim temperature. Vibration may also lead to fluctuating stresses such that the fatigue properties of the disc material are not without significance.

If the design is such that the rotor temperature does not anywhere exceed 550°C., then low alloy structural steels can be devised with the necessary properties both at the centre and at the rim. If the blade temperature rises, however, the rim temperature can become such that these steels are unusable and alloys must be employed of more complicated composition and with properties approaching those of blade materials.

Gas turbine rotors are relatively large and heavy, and must therefore be manufactured from ingots of substantial size.* The difficulty of obtaining sound porosity-free ingots is obviously greater the larger the ingot size, while forging difficulties are also increased. Heat treatment of bulky forgings, particularly when the more rapid rates of cooling are called for, is a serious problem, as also is the non-destructive examination and testing of a large mass of metal.

Sykes, Oliver and others [2], [3] have discussed these problems in some detail and shown how great the progress has been in solving them.

*Attempts have been made to make cast rotors, but with what success is not known.

3. THE NOZZLE GUIDE VANES.

The design stresses in nozzle guide vanes are relatively low, but additional stresses arise from thermal expansion effects. The thin sections of these blades are heated and cooled with extreme rapidity and the lack of uniformity of temperature during rapid heating and cooling is apt to lead to stresses which may cause cracking or buckling.

The operating temperature for nozzle guide vanes is higher than that of the moving blades and, whereas the latter are subject to a mean temperature arising from the series of combustion chambers, an individual group of nozzle guide vanes may operate above the mean temperature because of inaccurate balance between the various flame tubes.

As a result of these considerations it is clear that resistance to scaling is of considerable importance in nozzle guide vanes, while resistance to cracking and distortion under sudden and uneven heating and cooling is likewise important. Nozzle guide vanes are not required to resist high stresses for prolonged periods and in this connection the requirements differ from those in rotor blades. This in turn renders it possible to contemplate the use of castings and considerable importance attaches to the matter of whether a material can be cast satisfactorily into thin sections.

In some designs where wrought materials are preferred, the nozzle guide vanes can be manufactured in the form of cold rolled or drawn specially-shaped strip, a method of manufacture which is calculated to permit low cost mass production.

4. COMBUSTION CHAMBERS AND DISCHARGE ARMS.

A satisfactory material for flame tubes must obviously offer high resistance to scaling. Flame tubes do not operate at a uniform temperature and even in the best of the present designs some areas are likely to reach 850°C. Further, the location of these hotter areas may change with variations in the air/fuel ratio.

The conditions are such that stresses arise from thermal expansion effects and a suitable material must have sufficient high temperature strength to resist distortion and cracking under these stresses. Again, pulsations from the air stream and the flame lead to the development of alternating stresses in the flame tube so that resistance of the material to fatigue is considered necessary.

Combustion chamber parts must necessarily be made up from sheet metal so that the engine weight can be kept down. Accordingly, an essential requirement in suitable material is that it should have exceptionally good hot and cold rolling properties. Furthermore, since the parts are bent, drawn or spun, the alloy in sheet form must possess adequate cold forming properties. Flame tube assemblies are produced by spot and seam welding methods and the material must be suitable for the employment of automatic welding equipment.

5. PROGRESS IN SOLVING THE PROBLEM.

Such were the high temperature material problems that the gas turbine engineer presented to the metallurgist in the years just preceding 1939, and it may be of interest briefly to indicate what appears to have been the line of development in some of the interested countries up to the present time.

(*a*) *Great Britain.*

Interest in the mechanical properties of alloys at temperatures above 600°C. resulted in research being initiated at the National Physical Laboratory around the year 1923. This had indicated that nickel-chromium and nickel-chromium-iron alloys might not only exhibit their well-known oxidation resisting characteristics, but might also have useful creep-resisting qualities in these high temperature ranges.[4]

In the case of alloys for the gas turbine, pioneer work was done by the late Dr. W. H. Hatfield and his team of workers at the Brown-Firth Research Laboratories. Hatfield's attention naturally turned to the creep-properties of the austenitic steels, and in 1938[5] he drew attention to the high temperature possibilities after heat treatment of one of these steels containing about 8 per cent. nickel, 18 per cent. chromium, 1 per cent. titanium and 1.5 per cent. aluminium. A steel similar to this, known as "Stayblade," was in fact tried for turbine discs and blades in early jet propulsion engines.

Further research led later to the production of the complex austenitic steel "R.ex 78," of which the following has been given as a typical composition:—

C.	Si.	Mn.	Ni.	Cr.	Cu.	Mo.	V.	Ti.
%	%	%	%	%	%	%	%	%
0.12 max.	1.0 max.	1.0 max.	17-18.5	13-14.5	3.5-4.5	3.5-4.5	0.25 max.	0.5-1.0

This steel, after suitable heat treatment, possessed high temperature properties in advance of any other material then available and, used for rotor blades with "Stayblade" for the disc, brought within reach a workable jet engine. Details of the development of "R.ex 78" were recently given by Dr. Sykes, Dr. Hatfield's successor.[2]

Unfortunately, although a jet engine could be operated with "R.ex 78" blades, the properties of the alloy in 1939 were not quite sufficient to allow of those stresses and temperatures being employed which were needed for the efficiency of the turbine engine to compare favourably with that of the then existing piston engines.

At about the time of the outbreak of hostilities the author's organisation was asked to turn its attention to this question of alloys for use under stress at high temperatures and 750°C. was specifically mentioned. The whole of the available data were carefully reviewed and it was concluded that the most promising line to follow was to investigate the possibilities of alloys based on the well-known 80/20 nickel-chromium alloy.* Not only had this alloy shown promise in the N.P.L. work, but a long experience existed in its production and fabrication. A forgeable alloy was considered essential at that time, and it was known that the nickel-chromium alloys could be worked under the hammer and in the rolling mill.

Within a period of months it was possible to report to the Air Ministry that an alloy (subsequently named "Nimonic 75") was available which, after having been given suitable heat-treatment, provided the required properties at 750°C. By that time, however, the principal interest had moved to lower temperatures, and "Nimonic 75" did not show up as favourably at, say, 650°C. as it had at 750°C. The incident is worth recalling since it indicates the importance of the metallurgist being provided with an exact knowledge of the engineer's requirements and especially of the temperature at which it is the intention to operate. The time in this particular instance was in fact not altogether

*Employed extensively for heater elements and other high temperature uses because of their resistance to oxidation.

wasted since "Nimonic 75" has proved to be the most satisfactory alloy for combustion chamber components.

"Nimonic 75" owed its creep resistance to the effect of heat treatment on the solution and precipitation of carbides of titanium. The research done during this development showed that titanium in the comparative absence of carbon could, if an appropriate heat treatment were followed, give the nickel-chromium alloys considerably improved high temperature properties at 650°C. as well as at 750°C. Aluminium could also assist. Much work was necessary to determine the optimum titanium and aluminium contents for providing the best balance of high temperature properties and an adequate degree of forgeability. The optimum temperature and time for the solution-treatment on the one hand, and for the "precipitation" treatment on the other, had also to be worked out. The final composition arrived at was within the range given below:—

C.	Si.	Mn.	Fe.	Cr.	Ti.	Al.	Ni.
%	%	%	%	%	%	%	
0.1 max.	1.0 max.	1.0 max.	5.0 max.	19-22	1.5-3.0	0.5-1.5	Balance

From this, after a heat treatment consisting of soaking for 8 hours at 1,080°C., air cooling, re-heating for 16 hours at 700°C. and re-cooling, creep properties were obtained substantially higher than those of any other material then available. The new alloy was called "Nimonic 80" and Fig. 8 gives some indication of the extent of the advance which had been made.

There followed a period of intense effort to determine the conditions under which the alloy could be produced in quantity by normal works' methods. No alloy with quite

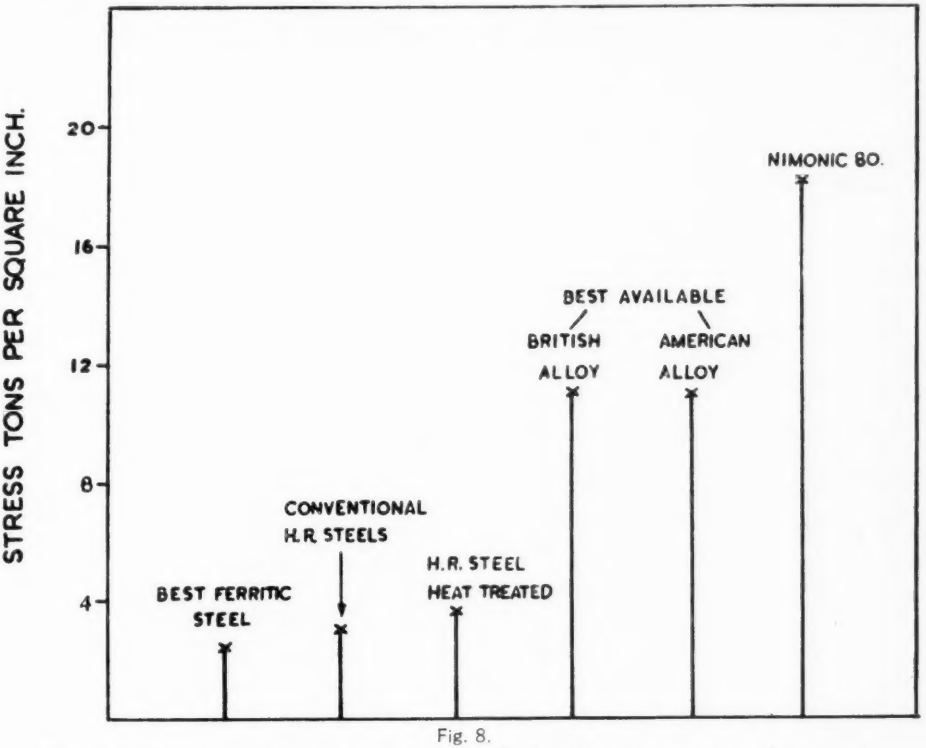

Fig. 8.
Trend of improvement in creep resistance up to 1940-41 on basis of stress to give 0.1 per cent. in 300 hours at 650°C.

these high temperature properties had previously been processed in quantity on a works' scale, the ingots having to be reduced by forging and rolling to dimensions approximating to those of the finished rotor blade. There were many disappointments before it was possible to assure the Ministry of Aircraft Production that "Nimonic 80" could safely be specified and would meet the exact inspection required of such a vital component as a rotor blade.

The first trials were made early in 1942. Since that time "Nimonic 80" has remained the standard material for aircraft rotor blades in engines produced in Great Britain. Experience has naturally improved the quality of the alloy and the ease with which it can be produced. Since they have not previously appeared in any general publication, a summary of its properties is given in an Appendix.

Research on blade materials has continued and still higher quality materials are now available, at least in experimental amounts.

The higher rotor speeds and service temperatures, made possible with "Nimonic 80" blades, called for improved properties in the rotor, particularly at the rim. About this time the work of Oliver and his associates became known. This, as has been described by Oliver and Harris,[3] had involved a study based on the well-known aero-engine valve steel which, conforming to the Air Ministry's specification DDT.49B, has a composition of nickel 13 per cent., chromium 13 per cent., tungsten 2.5 per cent. and carbon 0.5 per cent. The research resulted in a new alloy, "G.18B," being developed with the general composition of:—

C.	Mn.	Si.	Ni.	Cr.	Co.	W.	Mo.	Cb.
%	%	%	%	%	%	%	%	%
0.4	0.8	1.0	13.0	13.0	10.0	2.5	2.0	3.0

After being soaked at 1,300°C. and "subjected to plastic deformation at a temperature in the range 650°-800°C." it provides adequate properties for use as the rotor disc and has been used since 1942 almost exclusively for this purpose in British engines.

Work on the "R.ex 78" type of composition has also been continued and Sykes has recently published properties of an improved alloy, "R.ex 337A"* which indicate that it might prove a most satisfactory rotor material.

A variety of materials has been used for nozzle guide vanes. In the early jet engines "Stayblade" was used. Subsequently, rolled and cast "Nimonic 75," rolled "G.18B," cast "Vitallium" and cast "H.R. Crown Max"†[6] have all been tried and are still being used in one or other design of engine. Where the conditions are particularly severe "Nimonic 80" is now used.

Flame tube assemblies were first made from heat-resisting austenitic steels which were then available in sheet form. Later "Inconel," a nickel-base alloy containing chromium and iron, was used for a brief period. When "Nimonic 75" was developed early trials indicated its particular suitability for these components, and although an alloy of this type had never previously been produced in quantity in sheet form, it was ultimately found that it could be made available in satisfactorily thin gauges and with a suitable surface finish. It proved amenable to the welding technique employed in making up combustion chambers and so on, and has become the standard alloy for the purpose in British engines.

This brief account of British developments would not be complete without reference to the large number of parts of the gas turbine engine the materials of which, although not requiring the high temperature strength or oxidation resistance of those mentioned above, must possess definite high temperature resistance. Hall[6] has described the use of the various austenitic steels for these components.

(*b*) *United States of America.*

As in Great Britain, intensive research on high temperature alloys was made in America during the war years. The initial interest was in finding a blade material for use in the exhaust-driven superchargers which were employed on the American military aircraft. The ease with which large quantities of these small supercharger blades could be produced to finished size by means of the "lost wax" casting process, turned attention to "Vitallium," an alloy which had been used for making special small castings by this method. "Vitallium" proved to have quite adequate properties for the purpose.

*loc. cit.

†Typical analysis C. 0.22, Si. 1.6, Mn. 0.4, Cr. 23.2, Ni. 11.8, W. 2.9 per cent. See reference 6.

When in 1941 the advances resulting in the Whittle engine were disclosed confidentially to the American Services, the scope of the work was extended considerably. The availability of a large number of laboratories having the necessary facilities and staff resulted in a wide range of alloys being investigated. This differed from the activity in Great Britain where, after the preliminary investigations which covered a very broad field, it was decided purposely to concentrate attention on a few alloys and bring them to production scale rather than dissipate the efforts of the few people available for the work on a variety of materials.

The need for urgency inclined the Americans to make much use of a "time-to-rupture" figure in their initial investigations and the influence of the previous interest in supercharger bucket alloys resulted in a wide adoption of 1,500°F. (815°C.) as the test temperature, although it was early appreciated that the temperatures of the blades in jet engine gas turbines rarely at that time exceeded 650°C. Later, the importance of obtaining creep curves at the temperature of service was accepted, but for some time there was difficulty in comparing the British and American work.

Extensive programmes organised by committees working for the Service Departments resulted in data being obtained on a wide range of alloys. This range covered austenitic chromium-nickel steels modified by the addition of molybdenum, tungsten, niobium, titanium, manganese, and so on, some with low and some with high carbon content, nickel-cobalt-chromium-iron alloys to which various additions were made, nickel-molybdenum alloys, precipitation hardened nickel-chromium-cobalt-iron and nickel-chromium-iron alloys not unlike "Nimonic 80," cobalt-base alloys such as "Vitallium" and the "Stellites" and chromium-base alloys containing iron and molybdenum. Details of the alloys and their properties have been published in a Symposium arranged by the American Society for Testing Materials.[7], [8], [9] Although a mass of information has thus been made available, the number of alloys actually used in engines appears to have been quite few.

The nickel-molybdenum alloy, "Hastelloy B" found favour for some time for rotor blades. There was continual interest, however, in the "Vitallium" type of casting alloy and, although there have been some disappointments, it is understood that these alloys are still used for some engines. In other designs K.42B heat-treatable nickel-chromium - cobalt - iron alloy has been employed, while in some cases successful results have been obtained with highly modified austenitic steels.

For discs the so-called "Timken alloy" containing 25 per cent. nickel, 16 per cent. chromium and 6 per cent. molybdenum, has been much used, while 19/9 DL, containing 19 per cent. chromium, 9 per cent. nickel, 1 per cent. molybdenum and 1 per cent. tungsten with additions of niobium and titanium, has been employed successfully in one design.

For nozzle guide vanes the "Vitallium" originally employed was later replaced to some extent by a 25-20 chromium-nickel-iron alloy, while for the combustion assemblies the nickel-chromium-iron alloy, "Inconel," has proved satisfactory. Heat-resisting steels of the 18/8 type have been employed for other sheet metal parts.

(*c*) *Germany.*

It is now clear that activity having for its aim the solution of the problem of high temperature materials for gas turbines was at least as great, if not greater, in Germany than any country before and during the war. Again, the major attention seems to have been directed to modified austenitic steels subject to heat treatment.[10]

When war came, the alloy first chosen as having the best properties consonant with alloy economy was "Tinidur," a steel containing 30 per cent. nickel, 15 per cent. chromium and 2 per cent. titanium. This was initially adopted for rotor blades but, as the nickel available for this purpose diminished, this steel had to be replaced by the inferior "Chromadur," another steel containing 18 per cent. manganese, 12.5 per cent chromium, 1 per cent. tungsten and 0.25 per cent. vanadium. Neither of these steels had properties approaching those of the alloys available to Great Britain and America and service temperatures and stresses had necessarily to be kept relatively low. Even so, engine lives were quite short.

The lowered temperatures permitted the use of ferritic steels for the rotors, and the German research certainly devised compositions and heat treatments which provided excellent properties from this class of material.[11]

Although the results of these researches may prove useful in other fields of application, there appears little that assists in solving the material problems of the present-day aircraft gas turbine.

No results of importance have so far been published regarding work in other countries on high temperature alloys. Such investigation has undoubtedly been made in France, the U.S.S.R. and Sweden, while in Switzerland there has been progress in the practical use of this type of material. The evidence at present available appears to indicate that Great Britain is well to the front in materials development.

CONCLUSION.

Although under the stimulus of war, alloys have been produced in quantity with properties far above those available to the engineer ten years ago, only a start had been made on the solving of this fascinating problem of high temperature materials for use in the gas turbine. Lack of fundamental knowledge on such questions as the nature of "creep" still makes alloy development laborious and time-absorbing. A vast amount of data on such properties as fatigue at high temperatures needs to be accumulated, after machines more closely simulating service conditions have been devised. Much has to be done, also, to relate the results of laboratory test with actual behaviour in service, since cost and the claims of production have seriously limited testing-to-destruction in actual engines.

Progress can only be accelerated by close and continual co-operation between metallurgist and engineer and by a clear understanding on the part of both of what the problem consists. The expenditure of much time and effort will undoubtedly be called for, but the success already achieved under the considerable difficulties always present when research and development have to accompany production pressure, promises that any such expenditure will be well repaid.

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APPENDIX.

"NIMONIC 80."

MECHANICAL PROPERTIES.

Mechanical properties depend on the condition and previous heat treatment of the material. The figures below are those for material in the fully heat-treated condition.

*Tensile** ($\frac{5}{8}$ in. dia. bar).

Temp. °C.	Modulus lb./sq. in. $\times 10^6$	0.1 per cent. proof stress tons/sq. in.	Maximum stress tons/sq. in.	Elongation per cent. on $4\sqrt{}$ area	Reduction of area per cent.
20	32.3	35	65	41	35
600*	27.7	34	49	15	20
650*	25.4	32	41	10	15
700*	24.8	30	38	10	15

*Rate of pull 0.5 tons/sq. in./min. in steps of 0.1 tons/sq. in. up to strain of 0.5 per cent., then 4 tons/sq. in./min.

Izod impact (120 *ft. lb. machine*, 10 *mm.* × 10 *mm. notched specimens*).

Condition of material	Energy to fracture at 20°C. ft. lb.			Energy to fracture at 650°C. ft. lb.		
Fully heat-treated	71,	67,	68	64,	61,	62
After 300 hours at 650°C. furnace cooled	43,	43,	41	50,	48,	47

Creep—Typical figures.

(*a*) 300 *hours data.*

Temp. °C.	Stress (tons/sq. in.) for following creep strains and rupture in 300 hours			
	0.1 per cent.	0.2 per cent.	0.5 per cent.	Rupture
600	25.7	29.3	31.3	32.3
650	19.0	22.0	24.0	25.7
700	14.0	16.5	17.8	19.2
750	8.5	10.0	11.8	12.5

(*b*) 1,000 *hours data.*

Temp. °C.	Stress (tons/sq. in.) for following creep strains and rupture in 1,000 hours			
	0.1 per cent.	0.2 per cent.	0.5 per cent.	Rupture
600	21.6	25.4	28.3	29.6
650	16.5	19.3	21.4	22.5
700	10.6	13.3	15.0	16.0
750	5.5	7.0	8.0	9.5

PHYSICAL PROPERTIES.

Specific gravity	8.2 to 8.25
Specific heat:	
30 - 100°C.	0.103 cal./gm./°C.
20 - 900°C.	0.128 cal./gm./°C.
Thermal conductivity	0.020 c.g.s. units at 20°C.
	0.029 „ „ „ 100°C.
	0.033 „ „ „ 200°C.
	0.037 „ „ „ 300°C.
	0.040 „ „ „ 400°C.
	0.044 „ „ „ 500°C.
	0.050 „ „ „ 600°C.
	0.056 „ „ „ 700°C.
	0.061 „ „ „ 800°C.
	0.066 „ „ „ 900°C.

Electrical resistance	115 - 125 microhms/cm.[3]
Mean coefficient of thermal expansion	
20 - 100°C.	11.7×10^{-6}
20 - 200°C.	12.5×10^{-6}
20 - 300°C.	12.8×10^{-6}
20 - 400°C.	13.4×10^{-6}
20 - 500°C.	13.6×10^{-6}
20 - 600°C.	13.9×10^{-6}
20 - 700°C.	14.3×10^{-6}
20 - 800°C.	15.0×10^{-6}
20 - 900°C.	15.7×10^{-6}

DISCUSSION

Professor Leslie Aitchison, *Fellow*: As one who had to deal with metallurgy as a whole, he was considerably interested in the way in which high temperature materials were drifting from the ferrous to the non-ferrous metals. They had certainly started with steel, but now they were going a long way from steel; there were alloys based on nickel, on chromium and other non-ferrous sides. It was interesting to note the way in which the ferrous metallurgists had adopted metals, and there was a considerable blending of the technique associated with both traditional non-ferrous techniques, and *vice-versa*. But he rather wondered whether they might not be approaching somewhat near to the limit of the possibilities of such a procedure. He believed they would not get much farther unless some real research work was done to find out, not only the fundamentals of creep, or the nature of creep in a metal, but to determine also the influence of various metallographical factors, the influence of the manufacturing history of the materials on their creep behaviour. They would have to do such work seriously if they were to avoid a long series of rather wearisome experiments, done on an *ad hoc* basis. Sir William had pointed out that the development of alloys such as he had described was an expensive process. One dare not ask how expensive, but it was obvious that considerable sums of money were involved, and those sums would not be lessened or the experimental times shortened until they possessed a much clearer knowledge of the fundamentals of the subject than they had so far gained. He supported strongly the view that more fundamental research was necessary.

He felt it might be necessary to go beyond the metals with which Sir William had dealt, if they were to meet the future requirements of the engineer. There were some metals of higher melting points than nickel, or even chromium, which might be used. Their development would require considerable work, but he supposed that Sir William would not rule them out on that account.

Sir William had said that he preferred that the materials should not be used under conditions which took them into the tertiary creep stage; he would urge that designers should be absolutely forbidden to use the materials under such conditions. He did not think the materials ought to be used under conditions which took them beyond the beginning of the tertiary stage, as indicated by the letter *N* in Sir William's Fig. 1.

The metallurgist should not be asked to devise a testing machine which would simulate practical conditions in the laboratory; if they were asked to investigate in that way they would have to embark on another series of *ad hoc* tests and spend much more money than could be afforded. It was far more important to ascertain the behaviour of materials in creep and in fatigue and so arrive at a full understanding of the problem.

A. G. Elliott (Rolls - Royce Ltd., *Fellow*): Sir William had given a comprehensive picture of the immense amount of work involved in developing the turbine blade materials and the materials for other engine components. From the engine designer's point of view, those materials were expensive to use, and in forging and working them they had to be treated with the greatest respect. He supposed that they had to face up to paying for all the expensive development work which had been done; but they had got to reduce the cost of turbine engines, which was still much higher than could

ultimately be accepted. It was difficult to give a direct figure for comparison, but the cost of the turbine engine was high compared with that of the piston engine.

The problems with which they were faced in using the materials were how to fabricate them and how to ensure producing consistent products. Difficulties of this nature were experienced in the handling of such materials at different forging plants, and every source of supply had to be carefully cleared by engine test; yet it could not be said that, having done that, they were out of trouble. The situation must be watched closely.

There had been unexpected production problems with disc materials. The turbine disc of, say, the Derwent I engine had been quite satisfactory; many had been made and were in service to-day. But with a slightly larger size of disc, such as that in the Derwent V, serious troubles had been experienced because of unsatisfactory material in the centre of the forging. The problem had to be tackled on practical lines, by running the discs up to bursting speeds, and then examining the fractures. One of the difficulties had been to collect the pieces undamaged. At first the pieces flew apart with tremendous momentum and buried themselves in the walls of the test pit, so that they had to be dug out from the earth several feet behind the walls. A means had been devised for recovering the specimens practically undamaged.

It was found that the solution of the manufacturing problem was to control carefully the work put into the forging of the discs. It was surprising to observe the small amount of difference in the dimensions of the blooms which affected the issue, and careful proportioning of the length/diameter ratio of the blooms had to be obtained. The same problem also applied to forgings for still larger discs.

All that meant that the engineer wanted to make his production problem easier, and it tended to lead him to consider simpler and less costly materials such as the more ferritic type, the non-austenitic steels, which perhaps might be designed into the engine. They would not stand the temperatures which the present austenitic steels would stand, so that a new design problem was involved. He would not like to say that the use of those materials should be discouraged for discs, wherever their use presented an advantage; he was merely pointing out some of the problems which still had to be faced.

The development of Nimonic 80 was a tremendous triumph. It contained a large quantity of nickel; looking at the tables in the paper, it seemed that all the best blade materials contained a large quantity of nickel, and one would like to congratulate Sir William Griffiths on that fact!

A good deal was being learned about Nimonic 80 and they were beginning to know what was its useful life. His Company had run a set of blades continuously for 500 hours on a turbine engine, at one temperature; it was also established that it would run for 200 hours only, before failure at another temperature, somewhere about 680°C. It was also known that the life of blades would decrease 90 per cent. for every 30° increase of temperature. This latter indicated how critical was the temperature factor, and how carefully the engineer had to use his engine or apply his practice so that the maximum temperature limits were not exceeded. It was leading to the use of such devices as automatic temperature control, which he believed would feature largely in the future.

He would like to see curves of rectangular hyperbola form giving the life of some of the materials under the conditions of temperature and stress obtaining in turbines; there should be enough information to-day from which to compute such curves from the immense amount of testing that had been done.

Sir William had referred to two Vitallium alloys, one containing 65 per cent. of cobalt and no nickel at all, and the other containing 33 per cent. of nickel and about 33 per cent. of chromium. What was the difference between those two Vitalliums?

Dr. H. Sutton (Ministry of Supply, *Fellow*): The information and resources of Sir William Griffiths and his team had been tendered most willingly and effectively from the early days of gas turbines for aircraft.

In the course of his own contact with this work the importance of a particular material being not merely an alloy but in every sense of the word an engineering material, had been strongly emphasised. Such materials must be capable of being manufactured from raw materials and fabricated into the shapes and forms desired on a considerable commercial scale and with reasonable consistency of behaviour during fabrication, as well as in subsequent use. Close contact over the years of these

developments had impressed him with the importance of manufacturing technique, really something akin to an art when these special alloys were concerned. The steady and progressive improvements in properties of the Nimonic alloys described by Sir William had borne eloquent testimony to the great benefit to be gained by progressive experiment and development integrated into improved metallurgical handling of the manufacturing processes. He knew that Sir William himself had held realistic impressions of the scope in this field but he was not sure that such impressions had been sufficiently appreciated by the technical world generally in relation to high temperature alloys. The achievements of the team represented by Sir William formed a standing example of the appreciation of the importance of metallurgical "finesse" in producing a good engineering material for high temperature service.

Sir William had mentioned, very appropriately, that exposure to high temperatures might facilitate changes which, even while not affecting life at temperature, might introduce dangerous brittleness or fragility in the cold. There were some experts who were of the opinion that alloys for use under stress at high temperatures should be stable at the working temperature, *i.e.* not liable to undergo constitutional changes. Francis B. Foley (*Metal Progress*, June 1947, p. 951) referred to the cast 26 per cent. Cr, 12 per cent. Ni alloy and mentioned that at 1,600°F. application of stress such as to produce 0.1 per cent. creep strain in 1,000 hours would produce fracture within a year. Did Sir William feel that constitutional changes, possibly facilitated by strain at temperature, tended to aggravate the loss of ductility that appeared to be shown when specimens fractured after long periods at a steady stress and at high temperature, a well-recognised feature of many materials?

Sir William had given them sound advice on the subject of stability. So far as his experience went, the high temperature properties of the cast alloys had generally not shown appreciable improvement by heat treatments of the type used with acknowledged benefit on many wrought alloys, beginning with a high temperature stage of treatment at a temperature much higher than the temperature of use. At the same time, the appearance of the micro-structures of the alloys did not impress the observer as by any means ideal from the point of view of offering high resistance to fracture under stress applied for long periods. In some cases lower temperature treatments might have given slight, but not very striking, improvement. The structural condition of most of the cast alloys seemed most unlikely to be easily transformed to one approaching equilibrium at operating temperatures of blades, for instance. Did Sir William feel that castings had received proper attention in these respects or that the high stress-resisting characteristics of the comparatively coarse-grained cast structures had encouraged investigators to overlook the scope for development of fine-grained structures that, while possibly not so good for high creep resistance under stress at high temperature, might give better long life characteristics? Several U.S. experts were, he believed, tending towards such ideas.

The development of Nimonic 75 sheet which they now knew to be a material of good workability, weldability, and so on, had been no less praiseworthy than that of the other products of the Mond Nickel Co.

A. H. Waterfield: He had listened with particular pleasure to the paper, having been for some years Secretary of the Ministry of Aircraft Production Committee to which the continually improving properties of Nimonic 80 were reported. It was remarkable how that alloy had seemed to improve almost month by month, and in a comparatively short time had become almost a different alloy.

He agreed that the lack of greater progress in the U.S.A., despite that country's enormous resources, was caused by a dissipation of energy; there were too many good alloys to test and the alloy producing firms had too many strings to their bows. Only concentrated effort such as had been undertaken by the Mond Nickel Company had enabled that firm to make the progress it had made, and congratulations were due to Sir William for the policy his firm had adopted and the inspiration he had given to his research team.

Having spent nearly a year in the U.S.A. with the British Commonwealth Scientific Office, he was particularly interested in Sir William's remarks concerning American alloy developments. It was curious that over there "Nimonic 80" and the corresponding American alloy seemed not to be more in demand. Metallurgists there were much concerned about low elongation at fracture, and

that was the main reason for the small use that was made of those alloys. They considered the low elongation after long periods to be a sign of over-ageing. Sir William had been careful to explain that the elongation figure was misleading; but one would like to hear the matter discussed further.

The position with regard to cast rotor blades was fluid in America just now, some firms changing from forged to cast blades and others swinging back; but there was strong pressure from the economic and strategic points of view towards castings. During the war the casting of exhaust buckets on a huge scale was misleadingly easy, what the Americans called a "cinch," and metallurgical technique, only now necessary, had not previously had to be developed. That lack of technique was exemplified by the inability of any U.S. precision casting foundry to guarantee the grain size in a blade. He had seen evidence that that technique would be developed and he felt fairly sure that a year or two hence if, as seemed probable, operating temperatures rose, most rotor blades would be cast. He would like Sir William's comments on the matter.

Even less had been said in the paper about the welding of blades to rotors. He had found no evidence in the U.S.A.—except a desire for rapid production—to support that practice, and despite much research the position was still unsatisfactory. Cracks occurred between the blades and, as they could not be prevented, they had to be tolerated. He believed the G.E. allowed them if they were radial and did not curl, and if they were not more than 3/32 in. long. Since the start of the crack was hidden by weld metal that seemed to be a dangerous criterion.

The objections to the welding of blades did not apply to the welding of composite rotors having a ferritic hub and an austenitic rim. That arrangement reduced the amount required of the expensive and difficultly worked creep-resisting alloy and used it in a relatively easily produced shape. The scheme was becoming increasingly popular and it seemed to have much to commend it, except the dangers of internal stress. He would be glad to have the author's views on that point also.

Dr. S. A. Main (Hadfields Ltd.) *contributed*: He was glad the author had emphasised the fact that under conditions of pure creep, ductility was not a criterion of a good material, because the question was one about which there had been much misgiving.

He would like to put it this way. As the author said, they had not yet a full and scientific understanding of the processes of creep, but they did know that to resist it they had to rely on the strength of the grain junctions. These were not capable of any appreciable separation without being disrupted, certainly not by an amount producing more than about one per cent. of permanent extension in the material as a whole. Until, therefore, a super-metal was discovered with grain boundaries so strong that breakdown was by slip within the grains as at ordinary temperatures, they must be content with this limitation on ductility.

They must get away from the natural idea —based on the inter-granular cracking which occurred under creep with overstressing—that the material was necessarily brittle. Some similar adjustment of ideas had already had to be made in the case of material overstressed in fatigue at ordinary temperatures, the characteristic fracture which inevitably, but wrongly, conveyed the idea of brittleness.

To operate with a margin of one per cent. or so of permanent extension between successful running and failure was certainly close work and against old ideas, but they had become reconciled to it in the case of fatigue stresses and should do so with creep.

D. M. Smith (Metropolitan-Vickers Electrical Co. Ltd.) *contributed*: Development experience on the jet propulsion engines with which he had been associated had shown the risk of inter-granular cracking occurring in the tertiary stage of creep. There had, however, been cases where turbine blades exposed to exceptionally severe conditions had reached the tertiary stage of creep without failure. This indicated the need for further investigation of the physics of inter-granular cracking, particularly in forms representing turbine blades, and for determination of the creep extension or other limit below which such cracking did not occur. This might be affected by the atmosphere in which the material operated Information of this type would be of the utmost value if it could be added to Fig. 7.

The author's remark that in gas turbine discs the most severe stresses occurred at the centre of the disc was questionable for the majority of turbine discs in aero-engine work. The combination of thermal stresses and centrifugal stresses seemed usually to give

maximum stresses at the rim. He did not know of any disc vibration having been experienced in gas turbines.

In the Beryl engines, which had air-cooled turbine discs, a ferritic material (molybdenum vanadium steel) had been used throughout and no trouble had been experienced. The material used exclusively in these engines for combustion chamber sheet metal had been Immaculate V, and this material had proved satisfactory in service.

N. E. Rowe (Vice-President, *Fellow*) *contributed*: There would be a problem of temperature fatigue as distinct from stress fatigue; Sir William referred to the latter in the course of this lecture, but not to the former. He showed curves to demonstrate what a fundamental effect variation in temperature had on the characteristic creep curve, so that if there were rapid variations of temperature in parts subjected to stress at high temperatures in a gas turbine there might well be a phenomenon of temperature fatigue.

SIR WILLIAM GRIFFITHS' REPLY

He expressed his appreciation of the kind remarks which had been made concerning the work done on high temperature alloys by the team of which he had been privileged to be the captain during the war period. He should say that his many pre-occupations at that time had made him almost a "non-playing captain," and the major credit for the devising of the alloys should really go to the research staff in the laboratories, of which Dr. Pfeil had been the head and Dr. N. P. Allen a principal member. The successful provision of the alloys in quantity for service had depended also on the sustained effort of a number of people, not only in the laboratory, but in the producing works and in the engine makers' plants. There had been many days of disappointment when one had been almost inclined to give up the task, and they owed much to the continual encouragement of the Ministry of Aircraft Production and particularly of Sir Ben Lockspeiser, Dr. Roxbee Cox and Dr. Sutton, who had maintained continued contact with the work.

In presenting the paper he had had to summarise to some extent. He hoped that he had provided some evidence for Mr. Elliott that the production of an alloy of this type was an expensive matter and he was sure that anyone connected with Rolls-Royce would agree that the cost of a high-class article should not be expected to be too low.

It was quite clear that work in this field was still at an early stage, and much remained to be done. He agreed with Professor Aitchison that the place of many metals in this application had still to be determined. At the same time, one required not only adequate strength from high temperature alloys, but also other characteristics. As he had attempted to explain, it was a combination of qualities which made a material suitable for this type of service.

In further reply to the discussion, he was pleased to note the agreement of Professor Aitchison and Dr. Main with the emphasis on the avoidance of the use of high temperature alloys in the tertiary creep stage. He was sure that many engineers appreciated the necessity of limiting the life of materials used under creep conditions, but in some years' experience he had gained the impression that this was not understood by all. Future investigation might determine just how far along the creep curve one could safely take the material in service but, until they knew much more than they did at present, he felt it essential to limit the life of any component working under stress at high temperatures.

He was glad also that Professor Aitchison had supported his plea for more fundamental work on this type of alloy. As he had tried to indicate, in the present state of their knowledge a great deal of effort was required to make even a small advance, and the possession of a greater insight into the fundamentals of the problem would be most helpful. Such data would also be of assistance in the conversion of a "good alloy" into the " good engineering material," available in quantity in suitable form, to which Dr. Sutton had referred.

He had not intended to suggest the development of a testing machine which would exactly simulate in the laboratory the practical conditions met with in service. He felt that it was necessary to accumulate more laboratory data on the combined effect of stresses simultaneously producing creep and fatigue, and to do this and to make progress with the development of improved alloys, machines more closely approximating to service conditions than the Wöhler or Haigh type machines were required. He agreed that the testing of materials in actual components, either in an engine or in a rig, was the most

helpful method of judging alloys. This was necessarily an expensive matter, particularly when parts moving at high velocity were concerned. The expense, however, might be justified. The development of blade materials, for example, had been slowed down to some extent by the small number of blades broken under known conditions which had been made available for examination by the alloy producers.

Mr. Elliott had commented on the point he had made in regard to the effect of temperature on life. He was not inclined to summarise this effect in quite the way Mr. Elliott had, although he recognised, and had indeed emphasised, the importance of not using an alloy, without previous trial, at temperatures much in excess of that for which it had been designed. Obviously alloys must be capable of withstanding the effect of a short-time fortuitous rise in temperature. Account of this should be taken in design. As far as possible, alloys needed to be "tailor-made" for each temperature range. He gave whole-hearted support to the use of automatic temperature control for keeping the component within that range.

Mr. Elliott referred to the use of nickel in the "Vitallium" type cobalt-base alloys. He believed it was true to say that nickel had beneficial effects in connection with transformations which took place in these alloys and minimised the embrittling effects that resulted therefrom.

Dr. Sutton asked whether constitutional changes tended to lower the extension at fracture shown when specimens broke after long periods at stress. They might well do this, but it was difficult to generalise since so much depended upon the nature of the constitutional changes and their effect on the resistance to fracture of, say, the grain boundaries to which Dr. Main referred. It would be possible for the changes to take place away from grain boundaries or, on the other hand, be confined to the neighbourhood of these junctions. Again, the inference was that they needed to know much more regarding the mechanisms of failure in creep, and particularly, as Mr. Smith had suggested, of what happened, after extended exposure to stress and temperature, as the creep approached and entered the tertiary stage.

Reference had been made to the grain size of cast heat-resisting materials. To produce cast blades it was necessary to introduce super-heated metal into a heated mould in order to reproduce satisfactorily the fine detail of the design. This naturally led to relatively slow solidification and a coarse crystal structure. The problem was again one of endeavouring to obtain the best results from two opposing effects, but in other fields much had been done towards refining the structure of cast materials and it did not seem too much to hope that a procedure providing a reasonable compromise might well be developed for turbine blade castings.

He felt it possible that the incompatibility of high temperature strength and forgeability might, ultimately, necessitate the making of blades by casting or powder sintering methods. Until other considerations permitted the use of temperatures requiring unforgeable alloys—and that time had not yet arrived—he would prefer to employ for a vital highly stressed part, such as a moving blade, materials which permitted the increased assurance obtained by the consolidation and uniformity of structure resulting from the hot reduction of a cast ingot of chosen size and shape, with the possibility of repeated inspection at the various stages of reduction. Low production costs were claimed for cast blades, but even if the claim were justified, he wondered whether the saving was of itself a sufficiently significant percentage of the total cost of the engine to justify the running of any risk with a component of such importance as a moving blade.

With regard to Mr. Howe's suggestion of "temperature fatigue," some attempts had been made to study the creep behaviour of materials under fluctuating temperature conditions.* Temperature fluctuations certainly took place in blades but he wondered whether their number and extent during the life of any reasonably designed engine could be at all comparable with those of the stress fluctuations—the number amounted to many millions—which might give rise to a "stress fatigue" failure.

It was true, as Mr. Smith said, that calculations indicated that the combined effect of mechanical and thermal stresses led

* The Cylic Temperature Acceleration of Strain in Heat Resisting Alloys, G. R. Brophy and D. E. Furman. Trans. Amer. Soc. Metals, 1942, XXX, No. 4, 1115-1128.

to maximum stress conditions at the rim, as compared with the centre of the disc. Opportunities for the alleviation of rim stresses, however, were provided by the broaching of the disc rim and by creep in the hotter zones. On the contrary, the temperature at the centre of the disc was normally relatively low and accommodation by plastic deformation could only take place at a high level of stress.

With regard to vibrations in the disc, it was intended that the reference should be to those alternations of stress which might arise from the blade vibrations and which might be of importance at notches in the blade root fixings.

THE ROYAL AERONAUTICAL SOCIETY

The 741st Lecture read before the Society—on 6th November 1947 at the Institution of Civil Engineers, Great George Street, London, S.W.1. In the Chair, the President, Dr. H. Roxbee Cox, D.I.C., F.R.Ae.S.

SOME RECENT DEVELOPMENTS IN THE LANDING GEAR FIELD

by

RENE LUCIEN, A.F.R.Ae.S.

Captain Lucien was the founder, with M. George Messier, of the Messier Company in 1927. *He took his pilot's licence in* 1922 *and from* 1927 *until M. Messier's death in* 1933 *he was test pilot for the Messier Company. Since then he has been Managing Director and Technical Director of the Company. In* 1936 *he was made a Chevalier de la Legion d'Honneur for exceptional services as an engineer and pilot to the French Air Ministry. From* 1936 *to* 1938 *he was a member of the Advisory Committee to the French Aeronautical Industry. During the war he served with the French forces. He has recently been elected President of the Airframe Committee of A.F.I.T.A., the French Aeronautical Society.*

INTRODUCTION.

WHAT are the particular factors of the aeroplane of 1947, which have a special effect on landing gear technique?

(i) Increase in the speed of take-off and landing.
1940: 65 to 90 m.p.h.
1947: up to 130 m.p.h.

(ii) Increase in wing loading and the use of thin or laminar flow wing sections.
1940: 30 lb. sq. ft.
1947: more than 50 lb. sq. ft.

(iii) Increase in physical dimensions and all-up-weight of the aircraft.
1940: 80,000 lb.
1947: 300,000 lb.

(iv) Increase in operational altitude.
1940: 10,000 to 15,000 ft.
1947: 15,000 to 30,000 ft.

These factors have a considerable influence on landing gear technique, giving rise to the following consequences:

(i) New conditions of operation.

(ii) Considerably increased strength requirements.

(iii) Complication of the retraction problem by the reduction of stowage space and the thinness of the wings.

(iv) The need for the operation of the equipment at extreme low temperature and in rarefied atmospheres.

(v) The evolution of "ground devices."

1. CONDITIONS OF OPERATION.

1.1. GROUND STABILITY—THE TRICYCLE LAYOUT.

We will not dwell on the advantages now universally accepted of the tricycle undercarriage layout. This layout presents two special problems:—

The shimmy of the nose wheel.

The increase in the nose wheel loading as compared with a tail wheel.

As regards shimmy, it is appropriate to examine the question of stability; the front wheel may have two different types of stability—static and dynamic.

(a) *Static stability* is obtained if the wheel is so placed in relation to its swivel axis that movement of the wheel out of the plane of symmetry of the aircraft tends to lift the latter. This stability becomes nil if the swivel axis is vertical.

(b) *Dynamic or drag stability* is obtained when the point of contact of the wheel and the ground is behind the intersection of the swivel axis and the ground. This stability is effective only when the wheel is in motion.

The practical solutions which are generally seen, taking into account these two factors, are shown on Fig. 1.

Until recently the general tendency of aircraft designers in France as well as in Great Britain, has been to use a freely-castoring

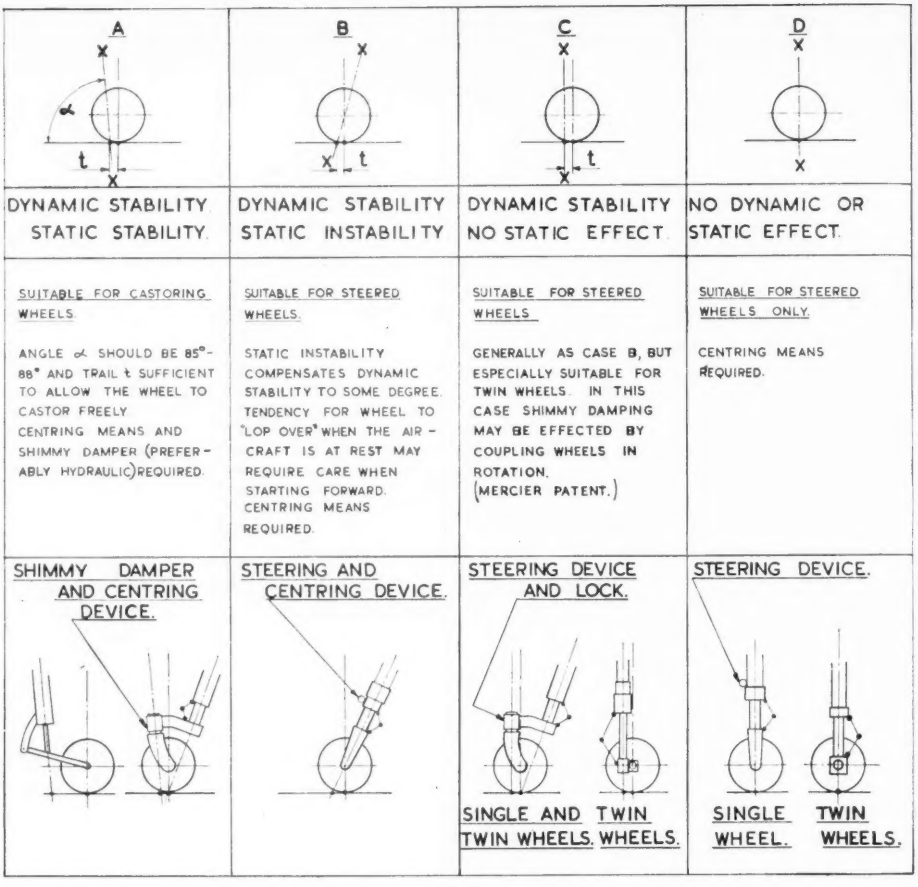

A
B
C
D
DYNAMIC STABILITY
STATIC STABILITY.
DYNAMIC STABILITY
STATIC INSTABILITY
DYNAMIC STABILITY
NO STATIC EFFECT
NO DYNAMIC OR
STATIC EFFECT.
SUITABLE FOR CASTORING WHEELS.
ANGLE ∝ SHOULD BE 85°-88° AND TRAIL t SUFFICIENT TO ALLOW THE WHEEL TO CASTOR FREELY. CENTRING MEANS AND SHIMMY DAMPER (PREFERABLY HYDRAULIC) REQUIRED.
SUITABLE FOR STEERED WHEELS.
STATIC INSTABILITY COMPENSATES DYNAMIC STABILITY TO SOME DEGREE. TENDENCY FOR WHEEL TO "LOP OVER" WHEN THE AIRCRAFT IS AT REST MAY REQUIRE CARE WHEN STARTING FORWARD. CENTRING MEANS REQUIRED.
SUITABLE FOR STEERED WHEELS.
GENERALLY AS CASE B, BUT ESPECIALLY SUITABLE FOR TWIN WHEELS. IN THIS CASE SHIMMY DAMPING MAY BE EFFECTED BY COUPLING WHEELS IN ROTATION. (MERCIER PATENT.)
SUITABLE FOR STEERED WHEELS ONLY.
CENTRING MEANS REQUIRED.
SHIMMY DAMPER AND CENTRING DEVICE.
STEERING AND CENTRING DEVICE.
STEERING DEVICE AND LOCK.
SINGLE AND TWIN WHEELS.
TWIN WHEELS.
STEERING DEVICE.
SINGLE WHEEL.
TWIN WHEELS.

Fig. 1.
Castor wheel layout.

nose wheel, the steering control of the aircraft being effected by differential braking.

A study of the use of transport aircraft, particularly at airports in the U.S. where traffic is intense, would seem to militate in favour of the general adoption of the steerable wheel.

The Messier Company has selected this system for the greater part of its designs.

For large aircraft it seems to be generally agreed that the use of a small independent steering wheel, mounted alongside the pilot, is the best means of control, although we have at times been asked to mount the steering wheel concentrically with, and inside, the main flying control wheel. The latter scheme seems at first sight the more attractive, but experience will show if the practical difficulties of the installation will overshadow the greater part of its excellent advantages.

For light aircraft, opinions differ on the advantages of coupling the steering control to the rudder bar or to the ailerons.

It is probable that solutions similar to that of the Ercoupe in the U.S. (nose wheel coupled to the control column which acts simultaneously on the rudder and ailerons) would be acceptable to those who have learned to fly on this type of aircraft, and where the necessary training is given, so that on landing the final turning of the front wheel into the appropriate direction for touch-down is done automatically.

On the other hand, many experienced

pilots, when making cross-wind landings, are unable to prevent themselves instinctively from operating the flying controls, thus causing damage to the nose wheel, or at any rate a violent swing on touch-down.

As an example, the mechanical designs which have been produced for two different nose wheels are described: the freely-castoring wheel, and the steerable wheel.

1.1.1. *Freely-castoring wheel.*

Figure 2 illustrates a freely-castoring nose wheel, self-centring being obtained by two flats on the nose wheel axis on to which two opposed pistons press under accumulator pressure. A selector permits the pressure of the accumulator to be applied or released at will. Restriction valves allow the free entry of fluid into both cylinders but restrict the exit of fluid from them, thus effectively damping out shimmy.

This system permits:—

(a) by releasing the pressure, unrestricted rotation through 360°,
(b) by applying a low pressure, a self-centring action and at the same time shimmy damping;
(c) by increasing the pressure, locking of the wheel in the fore and aft plane.

In addition it is possible by a simple means, for example, a valve connected to a pair of toggles joining the moving and fixed parts of the nose wheel shock absorber, to arrange that this increase in pressure takes place automatically as the load on the wheel decreases when the speed of the aircraft increases up to take-off. Fig. 3 illustrates an example of this type of system on the Dassault type 30.

Objections have been made that an anti-shimmy device along these lines is inadequate because it is only single-acting. On the other hand, during landing tests made deliberately without pressure in the centring mechanism, shimmy which was excited by some irregularity of the ground, was stopped without difficulty by applying pressure.

Information about the experiences of others which might confirm or refute these results will be appreciated.

1.1.2. *Steerable wheel.*

We have investigated several systems for steering the nose wheel, but will limit our remarks to the description of the particular one which has already been proved in service —and which has a simple servo-control—the follow-up action being by means of flexible cable remote controls or a rigid rod and lever

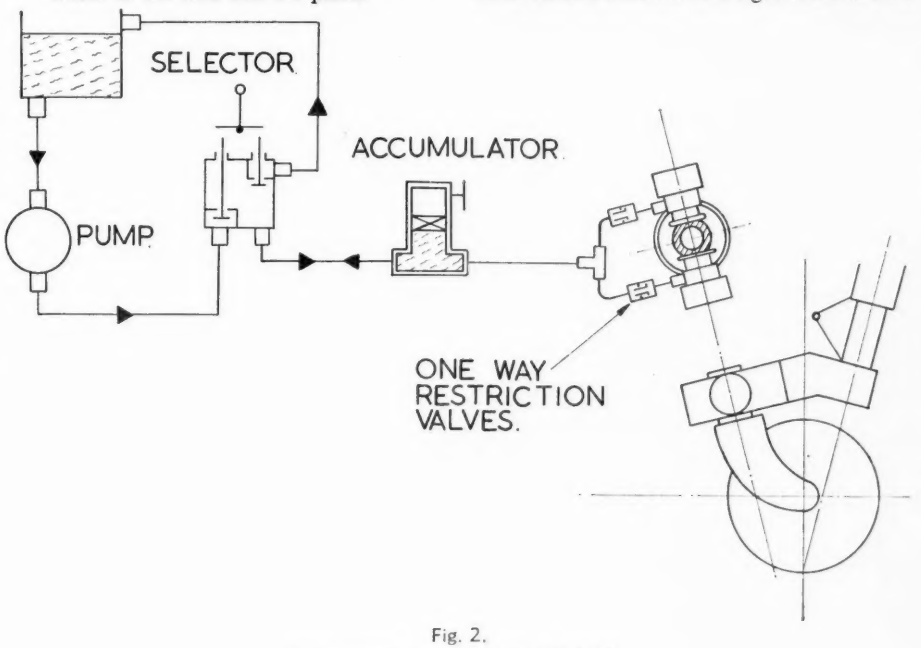


Fig. 2.
Freely castoring nose wheel (M.D.30).

Fig. 3.
The nose wheel of the Dassault M.D.30.

system. Fig. 4 shows a system of this type on a Breguet machine.

What we have done is to adapt to this new duty a system which had already been used with every satisfaction for preselective, follow-up flap control, and which has been found to give precise wheel steering control.

It would be appropriate to say a few words on the safety and flexibility of use which are achieved with this system.

We have provided the pilot with a small selector with three positions, as shown in Fig. 5, enabling the following three different conditions to be realised:—

(i) Servo steering by the use of the small auxiliary steering wheel.

(ii) Swivelling freedom of the nose wheel with a small centring action for stability and shimmy damping only.

(iii) Full castor locking.

To achieve this, the wheel fork swivel spindle carries a lever joined by two connecting rods to two pistons. Each of these pistons slides in other double-diameter pistons, as shown in the illustration. Each of these double pistons has limited travel from the central position. The volume between the two diameters of these pistons is connected to an accumulator set at a low pressure sufficient for centring purposes.

The cylinders of the smaller pistons permit both the steering control of the wheel and shimmy damping; it will be noted that a pair of one-way restriction valves creates the necessary damping out and appropriate filling up of the cylinders.

The operation of the system in the three cases referred to above is described briefly:—

(i) *Steering.*

Three points only need be mentioned:

(a) The pressure supply is from the normal hydraulic system.

(b) When the nose wheel and steering wheel are in phase the operating jacks hydraulically lock the nose wheel.

(c) The return to tank is made via the low pressure accumulator and a pressure maintaining valve, so that the accumulator is always under pressure.

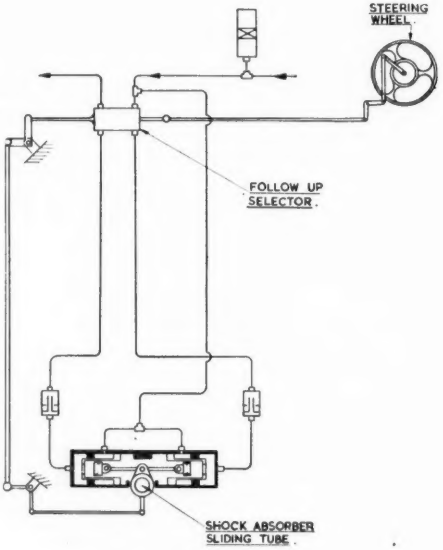


Fig. 4.
The steered nose wheel.

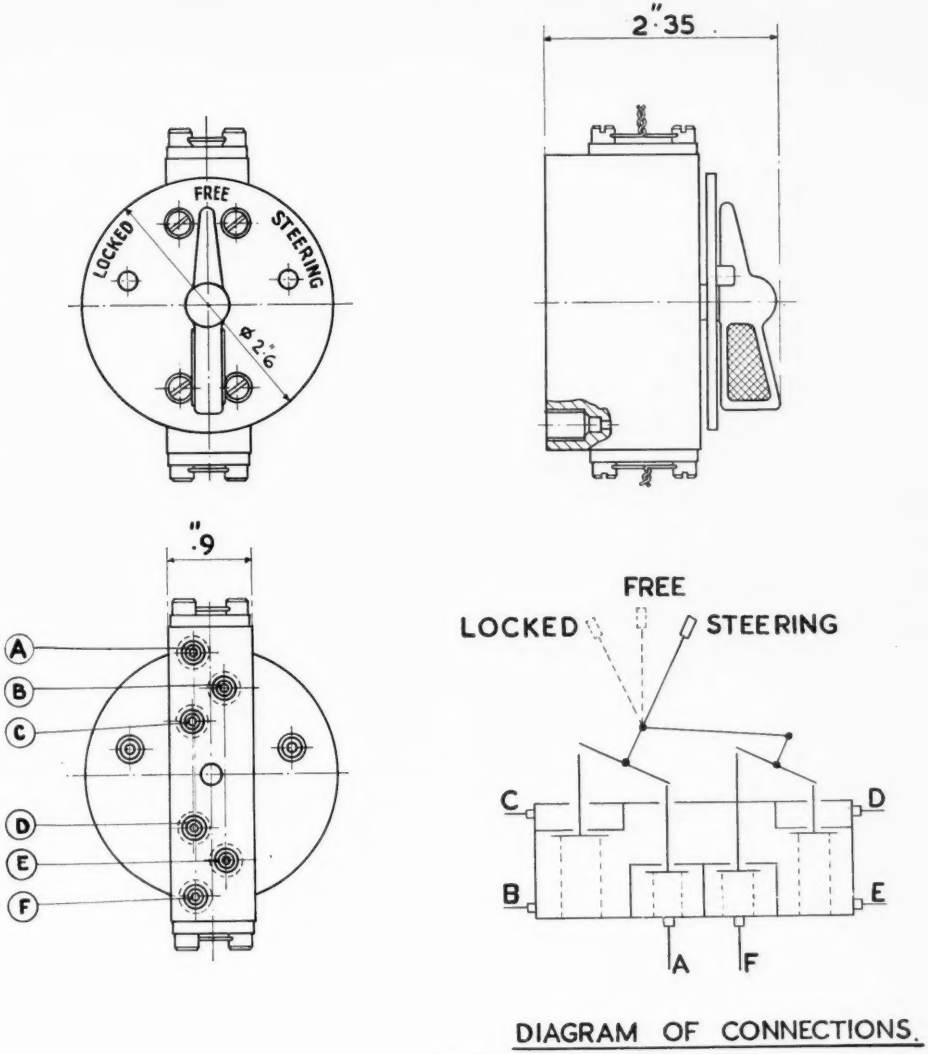


Fig. 5.
Three-position steering control selector.

(ii) *Swivelling freedom.*

To achieve this the pressure feed to the servo selector is interrupted and the two small steering piston chambers are connected to the low pressure accumulator.

Note that this manœuvre does not require the application of pressure, and that an abnormally low pressure in the main system automatically brings about this condition, allowing the pilot to manœuvre the aircraft by differential braking.

(iii) *Castor locking.*

This is effected by admitting emergency pressure which isolates the low pressure accumulator.

Finally it should be pointed out that if, during retraction, the wheel is automatically put in the second state, that is the steering is

disconnected, the wheel centres and the steering wheel is effectively isolated so that turning it will not operate the retracted wheel.

1.1.3. *Systems with all wheels castoring.*

Why has the castoring main wheel layout for light aircraft been so slow in finding support among pilots?

It was so natural a conception for the landing gear that Bleriot made use of it for his flight across the channel and had not to worry about the direction in which he should land. When runways were unknown the aircraft could choose its landing direction against the wind and the additional complication of the undercarriage was unnecessary. Then came the runways, initially used by the large heavy aircraft which were less sensitive to cross winds. Thus cross-wind landing technique became established and landing strips were often limited to two at right angles. But the light aircraft with low wing loading now finds itself in trouble and severe swinging on landing becomes likely.

The castoring undercarriage makes possible the general construction at low cost of many single strip private landing grounds, with much saving of space and money. It also makes possible a reduction in side load strength requirements and thus in the weight of the undercarriage.

We will not refer in detail to the construction of the castoring undercarriage, which is well known in this country from the pioneer work of MacLaren and has been developed recently in the U.S.A. by Goodyear, Firestone, and many others. Reference to this subject was made by T. P. Wright in his lecture on the "Personal Aircraft" at the recent Anglo-American Conference.

1.2. BRAKING.

Several circumstances have intervened to complicate considerably the problems of braking: —

(a) The increase in landing speed has an appreciable effect, since the kinetic energy to be absorbed increases as the square of this speed.

(b) The tricycle undercarriage layout on the one hand reduces to a negligible value the kinetic energy lost by air drag forces, and on the other hand permits a much higher brake torque, unlimited by overturning considerations.

(c) International requirements demand that an aircraft can be pulled up in a very short time in the event of an engine failure at take-off.

1.2.1. *French practice.*

These considerations have caused the French Service Technique to issue new braking requirements.

The latest French requirement is for a torque factor of 0.85 (=0.55g) in an extreme emergency, the tyre-to-ground coefficient of friction being assumed to be 0.65. (An explanation of the French "torque factor" is given in Appendix I.)

The application of this increased torque factor results in an appreciable increase in the dynamic load on the nose wheel and a consequent serious increase in the weight of this unit.

We have therefore sought for a reduction in this regulation and have been able to reach a compromise for future applications: —

(a) The energy absorption factor, allowing for losses due to drag, is to be taken as 0.9 for the tricycle undercarriage and 0.75 for the orthodox layout.

(b) A mean landing speed of 100 m.p.h. (160 k.p.h.) is assumed because standard wheels have been obligatory for many years with us.

(c) The normal brake control system generally uses pedals connected independently to the brakes on port and starboard undercarriages, and so arranged that the torque factor will not in any event exceed 0.7 (=.45g). It is also provided that the optimum value of the torque factor will be determined during prototype tests on each type of aircraft.

(d) The emergency brake control uses an independent source of pressure and duplicated pipe lines; it is arranged to operate at two different settings. The first position provides the normal brake pressure and torque; it is used in the event of failure of the primary system, or for parking. The second position calling for some special manœuvre and generally the breaking of a seal, corresponds to an emergency torque factor of 0.85.

Furthermore it is understood that this position is to be used in the event of real danger only and that loads may be applied to the undercarriage structure which exceed the proof strength.

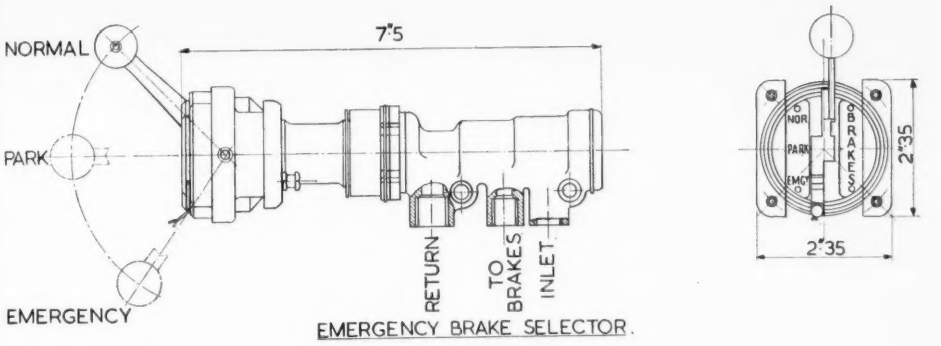


Fig. 6.
Emergency brake selector.

Consequently full inspection of the landing gear after an emergency stop will be obligatory.

Figure 6 illustrates a typical brake control lever meeting this new requirement.

1.2.2. *The modern brake.*

The need for tyres of the smallest possible diameter has led to the use of higher inflation pressures. While this has resulted in a slight increase in rim diameter for a given load, the width available for the brake is much reduced, because of the narrower tyre section, and the fact that the tyre scarcely overlaps the rim flanges.

In addition, the enormous evolution of heat has both forced an increase in the final permitted temperature of the absorbing mass (drum or disc), and has made it necessary to arrange the proper dissipation of the heat without affecting the tyre.

Nearly all modern brake designs use discs in place of drums for the following reasons:

(a) The drum when hot loses its cylindrical form and expands appreciably, thus upsetting the braking process.

(b) The drum dissipates heat from the wall opposite to that where it is generated, while with the disc it can be dissipated from the same surface on which it is generated.

(c) It is easier to isolate thermally the mass of the wheel from the disc than from a drum.

In practice, brake design inevitably means finding a satisfactory compromise between various contradictory factors:

(a) The disc or discs will become cooled the more they are exposed to circulating air. But a disc which is not protected in some manner will be subjected to damage by dust, sand or other foreign bodies, resulting in rapid lining wear.

(b) Use of very small specific lining area under high pressure gives the maximum exposure to the disc and therefore good cooling. On the other hand, an appreciable increase in the lining contact pressure makes the lining performance variable and inconstant, and increases the rate of wear.

(c) It would be interesting to allow an increase in the final temperature of the discs as this would save an appreciable amount of weight. But it must be remembered that a final mean temperature of 500°C. corresponds, during braking, because of the temperature gradient in the disc, to a considerably greater surface temperature; obviously the lining material must be able to resist such temperatures. With synthetic resin materials such temperatures would cause the distillation of the resin and possible combustion. The surface of the discs may be plated with hard chrome to increase abrasion resistance; however around 800°C. (the approximate surface temperature corresponding to a mean final temperature of 400°C.), chrome oxide will be formed having no mechanical strength and which will be torn off instantly.

These considerations indicate the disadvantages of using excessively thick discs.

To recapitulate: the modern brake should be designed around the normal qualities of constituents which at present can be obtained

commercially without difficulty, allowing scope for development as the technique of the production of the constituents themselves develops.

An example of a new French design of brake along these lines is shown in Fig. 7.

This design has good thermal isolation of the tyre, the rotary discs being driven by hollow cylindrical sleeves. The brake pads are spaced sufficiently to permit a good circulation of air across the discs, and they can be replaced simply without special tools.

1.2.3. *Aerodynamic braking.*

We will only mention this possibility briefly because in its realisation it falls rather far from the subject we are discussing.

Apart from reversible pitch propellers whose interesting possibilities depend entirely on the proper functioning of the engines, there is a need for finding means to effect braking aerodynamically to compensate for the loss in drag caused by the tricycle undercarriage layout. This is one interesting possibility of the use of variable incidence wings which have recently appeared on a number of aircraft, and which we ourselves provided for in an experimental aircraft we designed in 1941.

For example, an aircraft fitted with double

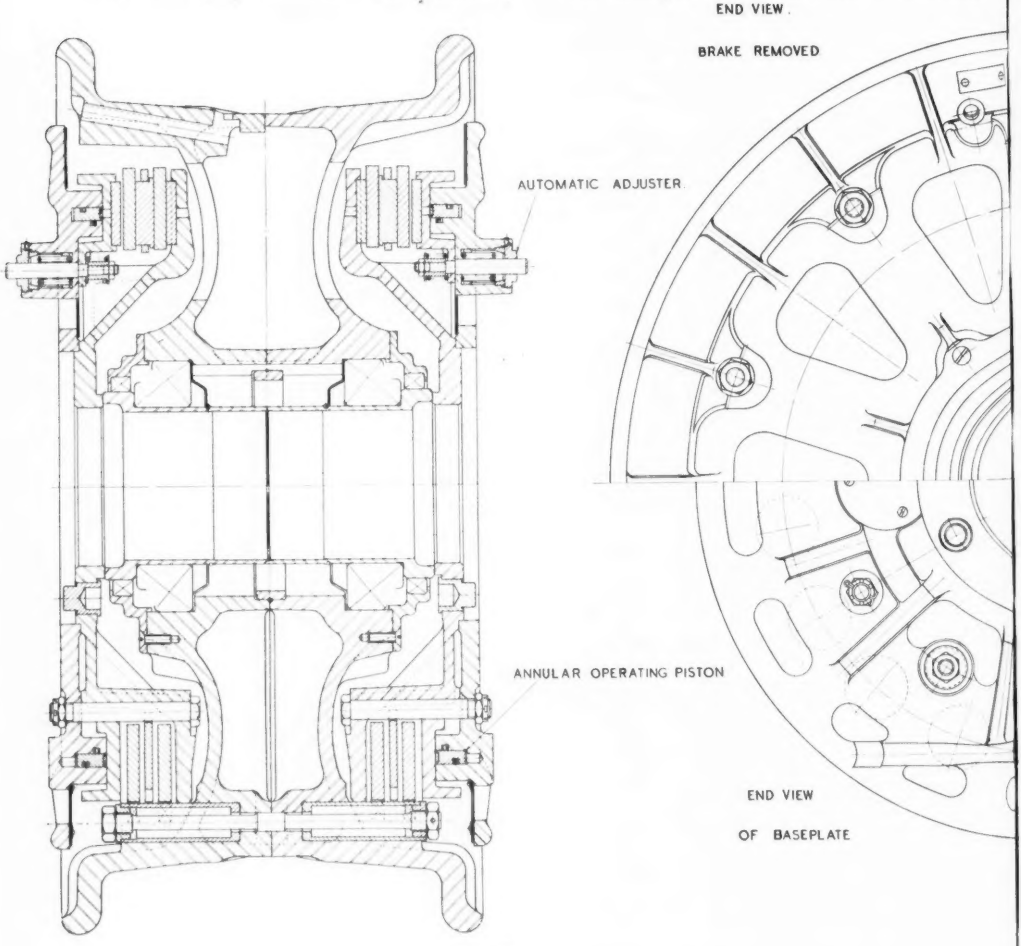


Fig. 7
A new French disc brake.

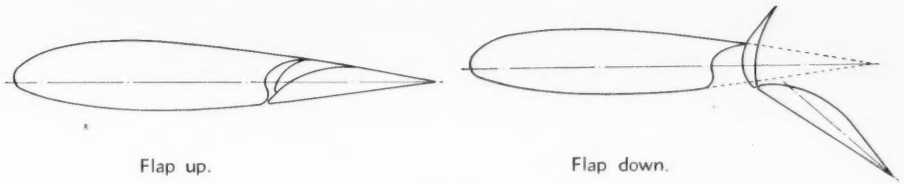


Fig. 8.
Aerodynamic braking by double flap.

flaps could have a considerable increase in drag by swivelling the intermediate flap, the movement simultaneously closing the slots and obstructing the flow over the upper surface of the wing.

1.3 SHOCK ABSORBER PERFORMANCE.

The increase in wing loading and, as a consequence, the raising of landing speed, results in making even more contradictory the qualities required in a good shock absorber:

(a) To absorb the maximum amount of energy at the moment of landing.

(b) To be sufficiently resilient, during taxying, so that excessive acceleration because of the inequalities of the ground are not transmitted to the airframe.

The first condition is met by the passage of oil under pressure through orifices so determined that the reaction developed does not exceed a required maximum. How can we make sure that this maximum force is not exceeded during fast taxying, since the irregularities of the ground can generate accelerations on the wheels which may actually exceed those of landing? Several engineers have studied this problem and three French systems are mentioned:—

The Chausson shock absorber (Fig. 9).
The Katz shock absorber system (Fig. 10).
The Messier shock absorber system (Fig. 11).

Experience will show if the claims of the first two systems are borne out in practice; if the need for double settings makes itself felt, we will make sure that the change-over takes place simultaneously on both sides. One proposed solution consists of using the brake control pressure for actuating this device.

The Messier solution (Fig. 11) has always been to use a shock absorber with additional orifice area provided over the central part of its travel, which is used during taxying. This variable orifice also enables efficiencies well over 80 per cent. to be obtained. We have found this system to be very satisfactory.

1.4. NEED FOR PROPER FUNCTIONING AT LOW TEMPERATURES.

The operation of aircraft at great altitude or in regions of extreme variation of temperature has introduced a critical new problem, particularly as regards low temperature. This problem affects the landing gear in various ways and in particular, in the influence of low temperature on the operating fluids (1.4.1) and on metals (1.4.2).

1.4.1. *Influence of cold on operating fluids.*

In considering hydraulic fluids it is necessary to examine them not only from the point of view of low temperature performance, but also from the standpoint of other factors which must be satisfied. Although in Great Britain you have standardised on a mineral oil in conjunction with synthetic rubber seals, in France some designers have remained faithful to castor base fluids. Our principal reasons have been the difficulty of obtaining a satisfactory synthetic rubber, and the better performance of natural rubber at low temperature.

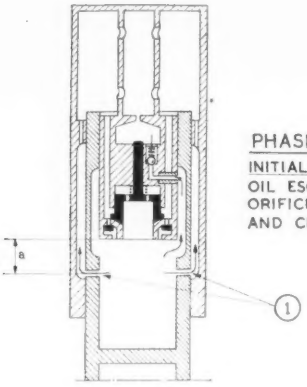
On the other hand, the needs of the day and, in particular, some recent accidents have concentrated research on the finding of a fluid with the following qualities:—

Freezing point below minus 80°C.
Flash point above 250°C.
Adequate lubricating qualities.
Freedom from toxicity at all times including when heated.

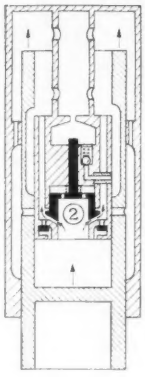
To our knowledge, no fluid in service meets those requirements.

We developed in 1940 a fluid which met the requirements of freeze point and lubrication. It consisted of a mixture of mono-ethylene-glycol, di-ethylene-glycol and methyl-glycol acetate.

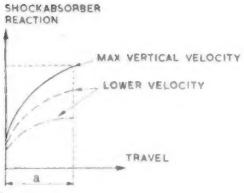
We abandoned the fluid because we considered the flash point too low. Recently we have concentrated our attention on silicate-base fluids and have evolved the basis of a

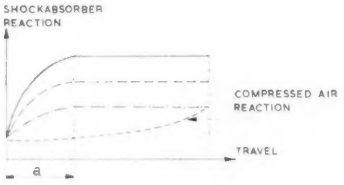


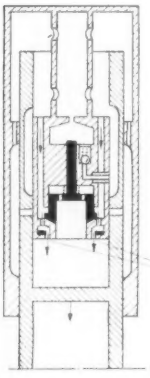
PHASE 1
INITIAL CLOSURE.
OIL ESCAPES THROUGH ORIFICE (1), VALVE BALANCED AND CLOSED.



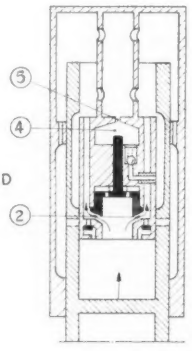
PHASE 2
FULL CLOSURE.
OIL ESCAPES THROUGH VALVE 2 WHOSE OPENING PRESSURE HAS BEEN SET DURING PHASE 1.



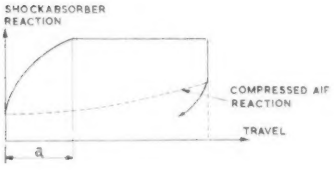




PHASE 3.
RECOIL.
RETURN OF OIL THROTTLED BY RECOIL ORIFICE (3).



PHASE 4.
TAXYING.
OIL ESCAPES FROM CHAMBER (4) THROUGH JET (5), ENABLING VALVE (2) TO OPEN; LARGE ORIFICES NOW AVAILABLE FOR EASY TAXYING.



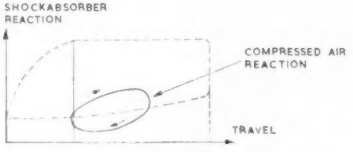


Fig. 9.

The Chausson Shock Absorber System.

This invention consists of an overbalanced valve which, while open to provide additional orifice area during taxying, is closed to restrict the orifice area during the initial impact. By allowing oil to leak out of a small chamber, there is a small time lag after touch down until the additional orifice area comes into action.

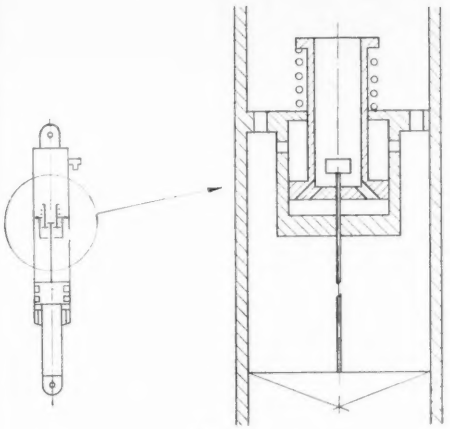


Fig. 10.
The Katz Shock Absorber.

This invention consists of adding to a shock absorber a valve which, while normally open to increase the orifice area during taxying (and thus "soften" the damping), is closed by extension of the leg at take-off and remains closed during initial impact. The valve operates as follows:—

Assuming the valve is closed by extension of the unit, initial impact creates pressure above the piston and this acts on the different diameters of the valve member, and keeps it closed against spring pressure. As soon as closure stops, the pressure in the main shock absorber volume drops and the valve can open.

fluid which appears to meet the full requirements, but long-range tests are needed. The obstacle in our present knowledge to the wide use of such a fluid is that of cost. We discount this factor however because:—

(a) The fluid, because of its inherent stability, is not likely to deteriorate in use and can therefore be filtered and regenerated.

(b) The general use of such a fluid would inevitably lead to a reduction in the cost of the constituents, which at present cause the fluid itself to be expensive.

(c) The question of safety, of prime importance in aviation, takes first place over other factors.

1.4.2. *Effect on metals.*

We will return to this question when the mechanical strength of the undercarriage is considered (2.2) in relation to the embrittlement of certain weldable steels at low temperatures.

It is sufficient for the moment to note that because of this, certain alloys, particularly

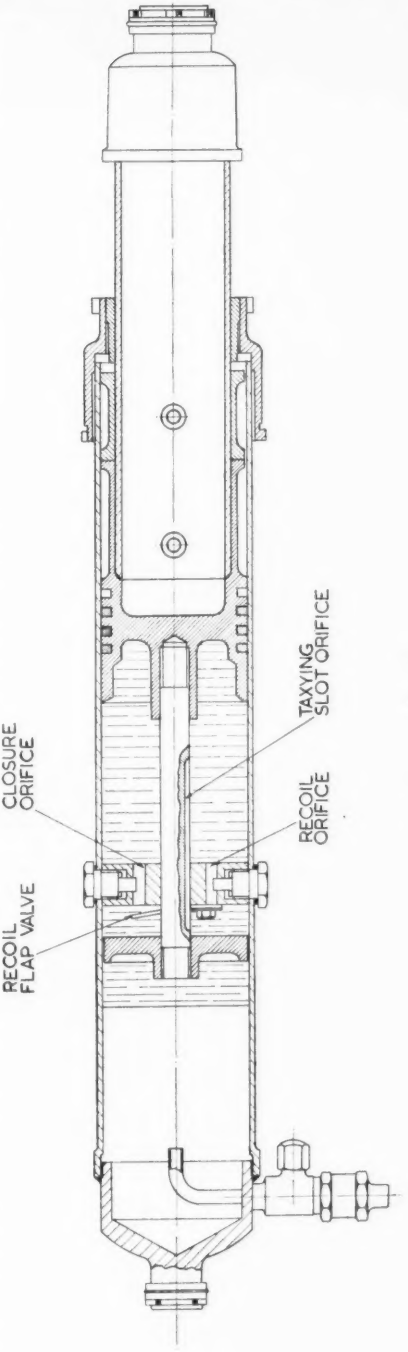


Fig. 11.
The Messier Shock Absorber System.
The Messier shock absorber uses a variable orifice area, additional area being provided over the central part of the shock absorber travel which is used during taxying.

carbon steel, should be avoided in the fabrication of parts which must operate at very low temperatures.

1.5. INCREASE IN SPEED OF OPERATION.

The increase in size of aircraft has resulted in a considerable increase in the length of pipe runs. This has resulted not only in an appreciable weight penalty, but also, in the case of hydraulic transmission systems, in a loss of speed of operation, due directly or indirectly, to the increase in pipe line friction losses. Rapidity of operation is of prime importance, particularly for undercarriage retraction at take-off; for this reason, for example, efforts are being made on the Lockheed Constitution to reduce retraction time from 30 secs. to 15 secs.

To gain both in weight and in speed of operation, we have adopted the following practices: —

(a) To improve retraction efficiency and reduce the variation in load as much as possible, we use compensators of various forms. These devices do not appreciably reduce inertia loading in the retraction gear because of vertical accelerations.

(b) Each organ to be controlled (jack, and so on), is provided with a hydraulic relay mounted close to it and using either a secondary relay hydraulic, or electric, system to effect remote control.

The principal advantages and disadvantages of the various methods of control will now be discussed briefly .

1.5.1. *Electro hydraulic solutions.*

Known methods made use of solenoid-operated, or electric motor-operated control valves. Solenoid types, in our opinion, have two disadvantages. The solenoid is certainly the heaviest device in relation to the work it can perform. Furthermore, if the solenoid is used directly to open a valve, it follows that the coil must be energised continuously for one position of the valve, consuming current and evolving heat. Otherwise mechanical complications must be introduced to eliminate these faults.

The various types actually used are described briefly.

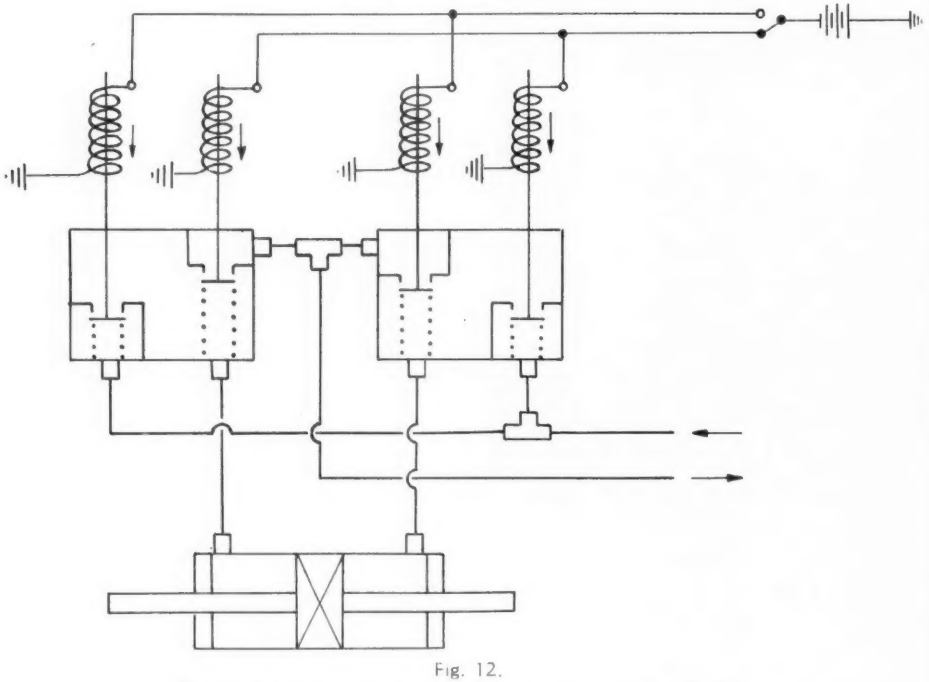


Fig. 12.
Electro-hydraulic selector-solenoid type continuously energised.

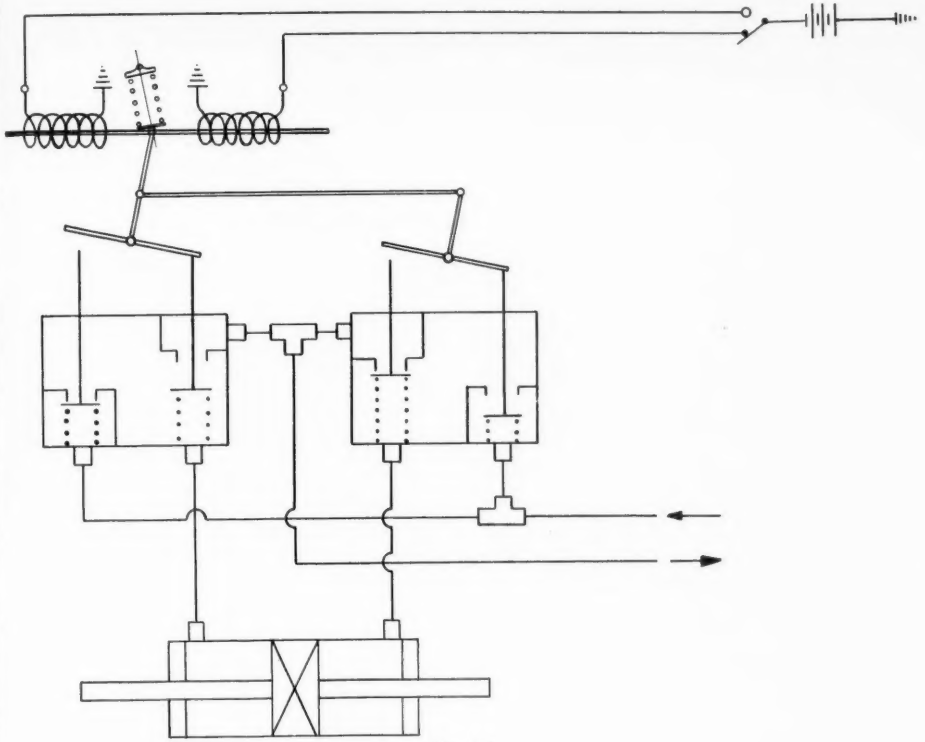


Fig. 13.
Electro-hydraulic selector-impulse type.

1.5.1.1. *Solenoid types.*

(*a*) *Continuously energised.*

Various solenoids open or close valves when energised, to control the jack as shown in Fig. 12. The continuous energisation of the coils can be avoided by using, for example, the open centre system popular in Germany, thus connecting both jack and pump freely to tank when all solenoids are de-energised. Such a solution has the advantage of eliminating thermal expansion effects but requires locking devices to maintain the jack in any required position.

(*b*) *Impulse.*

The solenoids cause the mechanical throw-over of the selector to lever either directly, or through opening small valves which control a small hydraulic jack.

1.5.1.2. *Motor types.*

Here a small high-speed motor is used to open and shut the appropriate hydraulic valves. The motors themselves are light and reliable. In practice, however, their use involves certain difficulties since, although the valve-opening mechanism must be stopped fairly accurately, the motor must not be braked too severely. Several means of getting over this difficulty have been proposed; for example, the Americans use a Maltese Cross mechanism; we have developed an automatic clutch which uncouples the motor when the valves are in the right position.

(*a*) *Continuous rotation.*

Each time the electric circuit is energised for example, by pressing a button, the motor rotates a small shaft through a reduction gear, the shaft carrying a cam and so on, to open and close the required valves.

This system is not considered sufficiently reliable because if, for some reason, the impulse is not sufficient the selector may not have operated properly and then the switch

may, for example, show "up" when the undercarriage is "down."

(*b*) *Reversing.*

We ourselves have adopted a reversing motor system with positive positioning for the following reasons:—

(i) Each position of the switch can correspond with an equivalent position of the selector.

(ii) The system gives an answer to all the difficulties to which we have already referred. Having tested various schemes we finally adopted a built-in limit and change-over switch operated by the selector cam mechanism, reducing to a minimum the number of wires required for control purposes. Also, as has already been mentioned, as soon as the motor has turned the selector mechanism half a turn it becomes declutched automatically and inertia shock loading is avoided.

An emergency hydraulic means of operating the selector if the current fails can be provided.

1.5.2. *Hydro-hydraulic solution.*

In parallel with the development of the electro-hydraulic valves just described, we have been evolving hydraulic relay systems, that is, a hydraulic selector controlled remotely by a small secondary hydraulic system.

To meet the requirements of the various aircraft designers we have produced selectors operated either by push buttons or by levers, the overall bulk being as small as possible to approximate that of an electric switch.

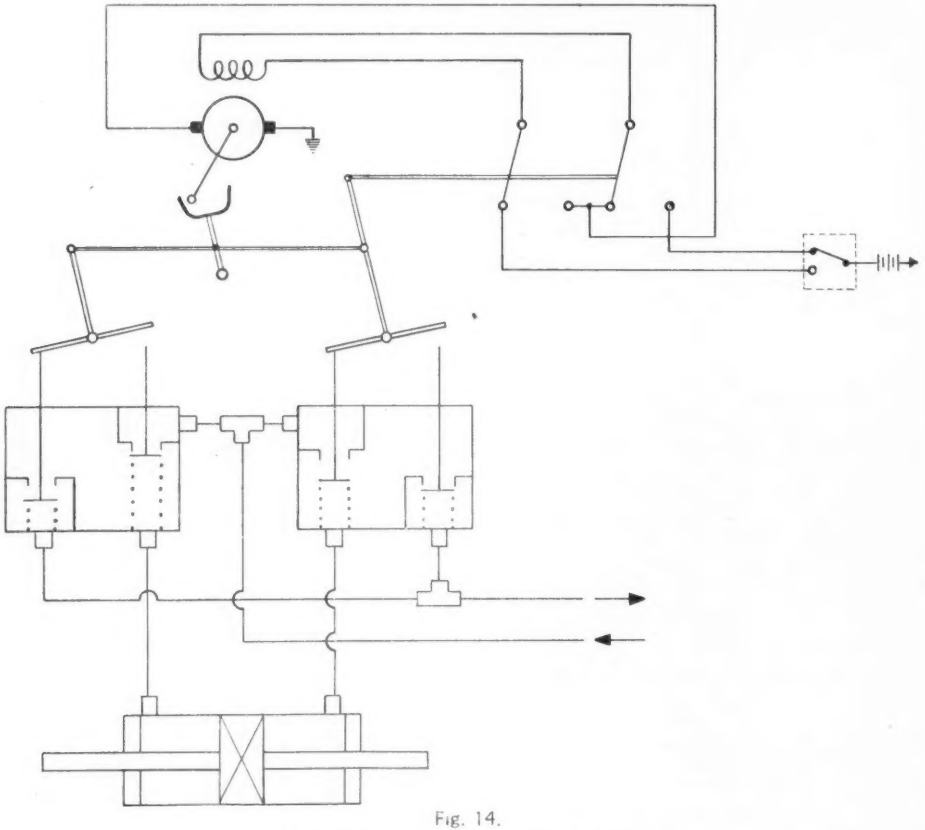


Fig. 14.
Motor driven electro-hydraulic selector.

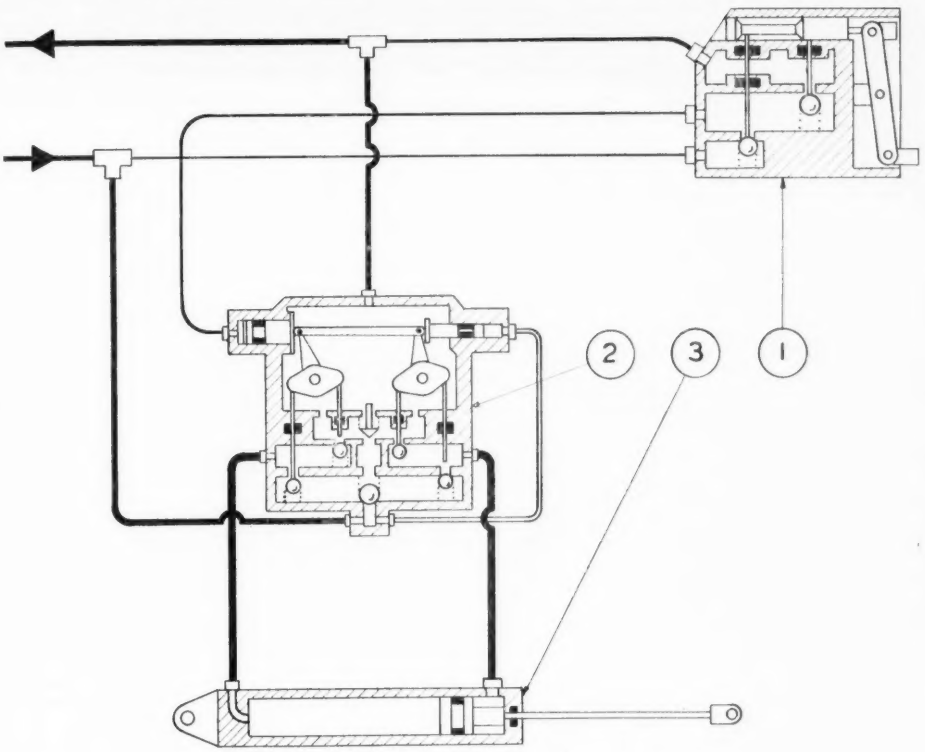


Fig. 15.
Hydro-hydraulic system.
1. Selector—2 button 3-way.
2. Relay selector—4-way—differential piston control.
3. Double acting jack.

These small units transmit signals, being required only to do negligible work, and consequently the pipes used—3/16 in. or even 1/8 in. are as light, small and as easily installed as electric wiring. This system for control of lengths up to 40 to 50 feet is as rapid, simple and light as the electro-hydraulic system.

1.5.3. *An opinion on the use of all-electric undercarriage retraction mechanisms.*

Most retraction mechanisms involve rectilinear motion, and it seems illogical to use a rotary motor and numerous gears in place of a cylinder and piston. On the other hand, one or two designs of very high quality, notably the F.W.190, are of interest. Furthermore, the use of high voltage alternating current may offer much better scope and possibilities than are at present available.

1.5.4. *Pneumatic solutions.*

These have not been made use of in France, principally for reasons of safety. The possibility remains, however, that results might be of interest if the operating pressure could be raised appreciably. Against this system can be set:—

(a) The enormous wastage of energy caused by compressing the air.

(b) The risk of icing.

(c) The weight penalty. If, on the one hand, one gains in eliminating the fluid, on the other hand, one loses on the equipment, as one cannot at present contemplate pneumatic pressures of 1,200-1,400 lb. sq. in. while hydraulic pressures, even at 4,000 lb. sq. in., are still increasing.

(d) The danger of compressed air which can cause serious accidents.

The possibility of supercharging the compressor from the main engine or turbine compressor naturally opens up new fields for the use of compressed air.

Electro-pneumatic problems are the same as electro-hydraulic ones.

2. STRENGTH REQUIREMENTS.

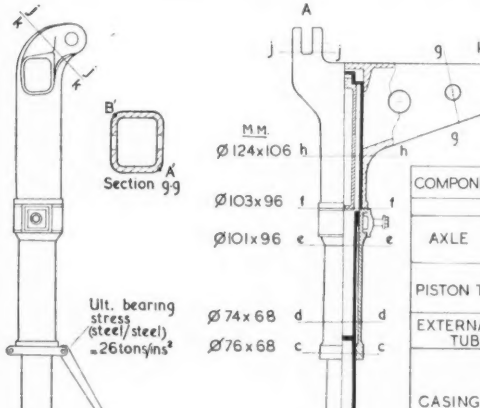
2.1. STRESSING CASE DEMANDS.

Each country has issued its own particular stressing requirements. Recently additional, and naturally enough not necessarily the same, requirements have been specified by I.C.A.O. How have these requirements been decided? We know that the great number of aircraft built, and therefore undercarriages broken during the war, both by the United States and Britain, has provided good statistical information on the strength of undercarriages. But these results have been obtained on a limited number of types of aircraft, each having particular characteristics or habits, and the conclusion can be drawn that a fault of a particular aircraft has been responsible for the increase in the severity of stressing cases applicable to other types of aircraft not suffering from the defect. Thus an aircraft which has a particular tendency to swing during taxying has been responsible for a revision of stressing cases to increase the side load strength of all undercarriages.

Furthermore, each country studies the requirements of other countries and frequently this causes further revision, obviously always in the direction of increased severity. The result of this type of long distance international co-operation on a purely theoretical level inevitably causes a continual increase in undercarriage weight.

The future development of stressing requirements should be based on systematic experiments where by varying a single factor only at a given moment, it will be possible to determine laws, or at least to draw envelope curves, which will give some idea of the extreme limit of loads to be applied to the various cases.

As an example, we have made an investigation into the application of the latest French stressing cases to an undercarriage of German origin manufactured in quantity in France since the Liberation, to meet immediate needs for civil communication.



COMPONENT	MATERIAL	ALLOWABLE STRESS lbs/in²	SECTION	STRESSING CASE	ACTUAL STRESS lbs/in²	RF
AXLE	STEEL CASTING	128000	a - a	X	238000	54
			b - b	X	204000	63
PISTON TUBE	STEEL	156000	c - c	X	277000	56
			d - d	X	235000	66
			l - l	X	287000	54
EXTERNAL TUBE	STEEL	156000	e - e	X	270000	58
			f - f	X	282000	55
CASING	MAGNESIUM CASTING	13450	g - g (A)	X	20200	66
			g - g (B)	X	16900	79
			h - h	X	45300	30
			j - j	Y	19000	71
			k - k	X	22600	60
			lug A	Y	18800	71
			lug B	X	15350	87
TOGGLES	STEEL	128000	ATTACH. LUG		107500	119

X = SIDELOAD OUTBOARD
Y = SIDELOAD INBOARD

Fig. 16.

The comparison of the N.C.701 undercarriage as flying and stressed to latest French requirements.

The undercarriages, used daily in more than 200 aircraft, refuse obstinately to be broken; Fig. 16 shows how far short of the official requirements they are.

As a conclusion we may express the belief that it would be in the general interest:—

(i) For requirements to be established on an international plan, based on systematic tests which would allow the cases to, at least, approach reality.

(ii) That each country arrange to use the internationally established requirement as a basis, complementing it, if it must, and even exceeding it, to meet its particular needs; but it is illogical for a designer to have to check to his own national requirements and then to have to check again against the 17 cases of I.C.A.O.

2.1.1. *Braking*: Repercussions on the structure and on the weight of the wheel.

We have already referred to the tendency to require that the aircraft can be stopped in the shortest possible distance in the event of an engine failure at take-off.

The use of a torque factor of 0.85 (that is, a deceleration of 0.55g) will cause appreciable velocity of movement of the undercarriage, particularly in the case of the nose wheel, because of the forward pitching of the aircraft when the brakes are applied.

This dynamic loading on the front wheel can lead to the use of a much larger wheel and tyre than would be needed to deal with the static load, and to an appreciable weight penalty on the structure.

Furthermore, as regards the main wheel, the increase in landing speed causes a serious increase in the weight of the mass which is used to store the landing energy on braking; one can without exaggeration say that wheel weights, as they have been known up to recent times, may be increased by as much as 15 to 30 per cent.

All these considerations have led us to believe that the conditions will be made less stringent in the future, by discounting the possibility of an eventuality which may never occur. It is thus of interest to study an emergency braking system which will not impose a weight penalty on the structure, nor complicate the brake system.

In this connection a method tested in the United States on light aeroplanes might be mentioned, which consisted of fitting the aircraft with a type of gun which at the moment of landing shot a "harpoon" into the ground attached to a cable; this cable was made from material similar to nylon which, when stretched, absorbed an appreciable amount of energy, the aircraft being stopped extremely rapidly, the whole retarding load being provided by the cable and taken on its fittings.

Such schemes obviously cannot be used on runways, but are of interest as an indication of what might be accomplished in the way of simplifying airborne equipment.

2.1.2. *Take-off and landing.*

We have seen that the loads caused by braking result in the use of a nose wheel tyre of excessive proportions. It seems appropriate to investigate means for making full use of the nose wheel tyre capacity provided to deal with the dynamic loads. To achieve this, means must be found to allow the aircraft to touch down on all three wheels (or sets of wheels), simultaneously. Here we must draw on the skill of the aerodynamicists to obtain a wing which, by varying its incidence or by the use of special flaps, or both, will allow the fuselage to remain horizontal for take-off and landing.

To take full advantage of this scheme the undercarriage shock absorbers must be put in balance, by hydraulic inter-connection, to eliminate pitching loads which occur when one wheel touches the ground first.

The advantages of this system are as follows:—

(i) The possibility of transferring part of the main wheel load to the front wheel, thus reducing the size and weight of the former.

(ii) The possibility of having all three wheels identical, with obvious advantages from a servicing point of view.

(iii) A reduction in the height and weight of the undercarriage, the propeller clearance alone being the determining factor; this also gives improved access to the aircraft.

(iv) Improved performance because of the fuselage shape being the optimum from the aerodynamic point of view, and uncompromised by considerations of take-off angle of attack, and with the wing attached to it in the appropriate setting for cruising flight.

(v) Improved take-off due to the propeller thrust line remaining continually parallel to the direction of motion.

(vi) Reduction in structure weight because landing loads are better distributed between all three undercarriages.
(vii) Improved braking since all three wheels can be safely braked.

The basis of strength calculations of undercarriages in almost all countries is the specification of an arbitrary drop height or vertical velocity, supposed constant or "airborne."

All dynamic tests in the U.S.A. as well as in Britain make use of free, and therefore accelerating, drops of the undercarriage which carries a mass above it.

In France we achieve truly representative airborne (constant velocity) drops by balancing the mass when it has reached the required velocity, generally by means of pneumatic cylinders.

With the British and American systems the mass dropped must be reduced to adjust the energy to the appropriate amount, bearing in mind that it will be that due to the total height (drop height plus deflection); with a long travel undercarriage the mass dropped may only be half to two-thirds of the correct mass, and we believe that the shock absorber orifices determined by this method will not be correct.

We would be glad to receive expert views on this subject, and to draw up a test programme to enable comparative tests to be made to settle this interesting problem.

2.2. THE BRITTLENESS OF METALS AT LOW TEMPERATURE—the case of certain weldable steels.

The exploitation of welding has led to the use of various types of steels, principally of the chrome-molybdenum type. Now the physical properties of some of these steels undergo considerable change at reduced temperatures. For example, some of the chrome-molybdenum steels have an impact strength of 20 kg. metres at normal temperatures, this becoming 8.2 at minus 78°C. and 1.5 at minus 188°C. As regards carbon steels, one particular variety has an impact strength at extreme low temperature of less than unity and the elongation at minus 188°C. is less than 2 per cent. Fig. 17, reproduced from a technical note of the Aero Sud-Est Company at Marignane, gives some interesting information on the subject.

REPRODUCTION OF TABLE SHOWING THE EFFECTS OF LOW TEMPERATURE ON CERTAIN STEELS

(Courtesy of The Aero Sud-Est Company, Marignane)

	Steel	Temp. °C.	Ult. strength × 1,000 lb. sq. in.	Proof strength × 1,000 lb. sq. in.	Elongation per cent.	Resilience*	Brinell
1.	Chrome-moly.	+ 20	114	95	21.8	22.2	234
	C = .22, Cr = .83	− 78	129	108		21.3	265
	Mn = .6, Mo = .22	− 188	172	164.5	22.4	1.1	329
2.	Nickel-chrome-moly.	+ 20	149	127.5	19.0	15.1	298
	C = .34, Cr = 1.88	− 78	171	143	20.4	11.5	336
	Ni = 2.27, Mo = .4	− 188	205	184.5	21.2	4.8	397
3.	Carbon	+ 20	60.5	36.5	37.0	27.2	120
	C = .08, Mn = .59	− 78	73.5	55	43.3	0.9	133
		− 188	114		1.2	1.1	229
4.	Carbon	+ 20	88.5	50	25.6	6.2	163
	C = .4, Mn = .78	− 78	105	71.5	23.7	0.9	182
		− 188	135		1.4	1.2	273
5.	Carbon	+ 20	113.5	58.5	18.7	less than 1	225
	C = .63, Mn = .75	− 78	128	65	18.5	„ 1	245
		− 188	145	143.5	approx. 0	„ 1	339

*Resilience is quoted in the original metric figure—*i.e.*, cm. kg./c.m.²
(From Table 3.2 of Aero Sud-Est note of 26th February, 1947).

Fig. 17.

Some of the chrome-molybdenum alloys suffer from a sudden drop in their shock resistance between minus 70°C. and minus 78°C. and their general properties at low temperature are somewhat unstable.

It is probable that some loss of properties will occur at even normal low temperature, depending on the composition of the steel.

To summarise, it may be said that the use of straight carbon steels should be avoided in preference to chrome-molybdenum or nickel-chrome-molybdenum alloys, chosen with circumspection, for the construction of welded steel undercarriage structure. American undercarriages use, in the main S.A.E.4130 and 4140 (chrome molybdenum) and for large massive parts, S.A.E.4340 (nickel chrome molybdenum).

2.3. The use of light alloy castings.

France has been the champion of the use of light alloy (principally magnesium) castings for undercarriage structures during the past twelve years. This technique is remarkably effective in the ready provisioning of complicated undercarriage members. It lends itself well to the rapid execution of the prototype, and is extremely economical for the small and medium production runs which are current in peace-time aviation.

It will be realised that this procedure demands a close watch on the characteristics of the metal and the manner of its use. As an example, in Appendix II is shown a reproduction of a typical foundry specification of a type which we in France find essential for the proper control of important castings. The specification is prepared, taking into account not only the strength required of the casting, but of the distribution of stress throughout it. Thus the highly stressed areas are specified on casting drawings sent to the foundry, and the test pieces are taken from these areas.

During the period immediately following the liberation of France a series of failures, caused mainly by defective inspection, led the Service Technique to make more severe the requirements of stressing and inspection applicable to castings, which have therefore lost some of their interest. Be that as it may, we believe that castings should not be used for undercarriage designs for aircraft of more than about 80,000 to 100,000 lb. because, even using heat-treated aluminium alloy, the sections necessary become excessively thick for proper casting.

We have calculated that, in the case of an aircraft of about 40 tons, stressed to French requirements, the weight of the undercarriage is sensibly the same, using light alloy castings or steel. On the other hand, if the weldable high tensile steel technique as used in the U.S.A. were used, casting would be shown to be at a disadvantage.

As regards the wheel itself, the magnesium casting remains standardised throughout the world. Fabricated steel wheels have been tried, but were found to be heavy. Forged light alloy wheels have found occasional use for simple shapes and where the very high die costs can be justified

2.4. Use of steels.

The general question of safety and the gradual increase in strength requirements are leading more and more to the use of integral steel undercarriage structures.

There have been two lines of development evident in recent years: one, originating in Germany, using steel castings welded to steel pressings and tubes; and the other, exploited mainly in the United States, making use of large stampings, with or without the use of flash welding.

2.4.1. *The German method.*

This method has the advantage of not requiring the large production equipment necessary for making large stampings. An indispensable feature of the method is the use of high tensile steel castings—castings which very few foundries are capable of producing properly.

The Swiss Company, G. Fischer, has built up a reputation for the production of such castings, often of very complicated shape, which experience has shown can be used with every confidence. Similar high quality castings are, I believe, being produced in England by David Brown and Sons Ltd. These castings are generally in a nickel-chrome-molybdenum alloy which welds well with other weldable steel alloys, with the reservation that the question of welding rod or of electrodes—always a delicate one—must be settled satisfactorily. It seems that certain German foundries succeeded, during the war, in producing castings with the same success, but if the Swiss Company requires a development period of several weeks for each new casting, it seems, from the information that we have been able to collect, that the equivalent period in Germany was often as long as a year.

The method however will allow the undercarriage to take various shapes convenient to the aircraft designer, particularly if pressings can be used as well.

The important point to know is the mean overall strength which can be achieved after fabrication and heat treatment. We in France doubt if it is possible to produce complicated structures whose strength can be guaranteed to exceed 130,000 to 140,000 lb. sq. in. This will indicate that if the combined casting and plate solution has advantages from the point of view of shape and ease of production of prototypes, it cannot rival, from a weight standpoint, the forged and welded solution used in the U.S.A. and which will be mentioned again. Fig. 18 shows a composite undercarriage made from high tensile castings and pressings for a Heinkel machine.

Designs produced entirely from pressings and machined bar parts are possible, as shown in Fig. 19, but are difficult to heat treat satisfactorily and make internal inspection of the welding virtually impossible because of the closed box section. On the other hand, this method can be very useful for quantity production if adequate safeguards to facilitate inspection are provided.

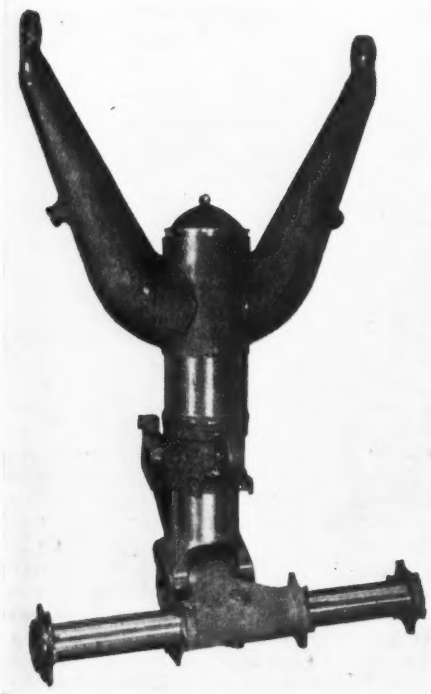


Fig. 18.
A Heinkel welded steel undercarriage.

Fig. 19.
A pressed steel radius rod.

2.4.2. *Steel forgings.*

It is now appropriate to consider the American method which is based on the use of forgings, machined and then welded together.

The principal feature of this technique rests in the fact that the steel alloys which are available in the United States allow remarkable physical properties to be obtained, even after welding.

Some information on the subject may be of interest, provided by two American firms who are currently employing the process—the Cleveland Pneumatic Tool Company, who

are undercarriage specialists, and the Lockheed Aircraft Corporation.

To quote the Cleveland Company:—

"The materials which we use to construct nearly all of our landing gear units are fabricated from steel of the chrome-molybdenum family, the greater portion of which are identified by S.A.E. numbers, such as 4130, 4140 and 4340. The latter is a chrome-molybdenum-nickel steel. These materials take welding operations very satisfactorily. When using arc, atomic-hydrogen, or oxygen acetylene welding methods, we use high-tensile welding material. This comes in the form of bars or rods of varying diameters and will produce a physical characteristic the equivalent of 80 per cent. of the parent metal being joined together when heat treated. Parts made in this manner and from these types of material lose approximately 10 per cent. of their resiliency when heat treated to a high tensile strength of 200,000 lb. per sq. in.

"To conserve the physical characteristics of the welding materials after making the weld or the joining of the parts, it is our practice to normalise the piece to relieve all stress and strain that may have occurred during the process of welding. After the normalising process, we reheat the parts to the required quenching temperature (in an oil quench) allowing same to cool after quenching to a temperature not to exceed 150°C. before placing into the draw or tempering furnace. This procedure is to ensure the equal distribution of the alloys, such as carbon, etc. In this manner, we experience no difficulties of retaining the elasticity of the metals at low temperatures."

Fig. 20 illustrates two undercarriage parts made from drop forgings placed in a flash welding machine and about to be joined together by an arc-heated pressure operation. The magnitude of the equipment involved will be appreciated.

The following information provided by the Lockheed Aircraft Company is also of interest, although differing in some respects from that given by the Cleveland Company.

"The steels used are the 4100, 8600 or 8700 series (S.A.E.) in practically all such structures, usually welded with low carbon welding rod, either torch or arc, or are electric flash-welded. Some use has been made of weld metal that will respond to heat treatment to a degree approximately the same as the components being welded together. This has not been the common practice in America thus far and has generally not

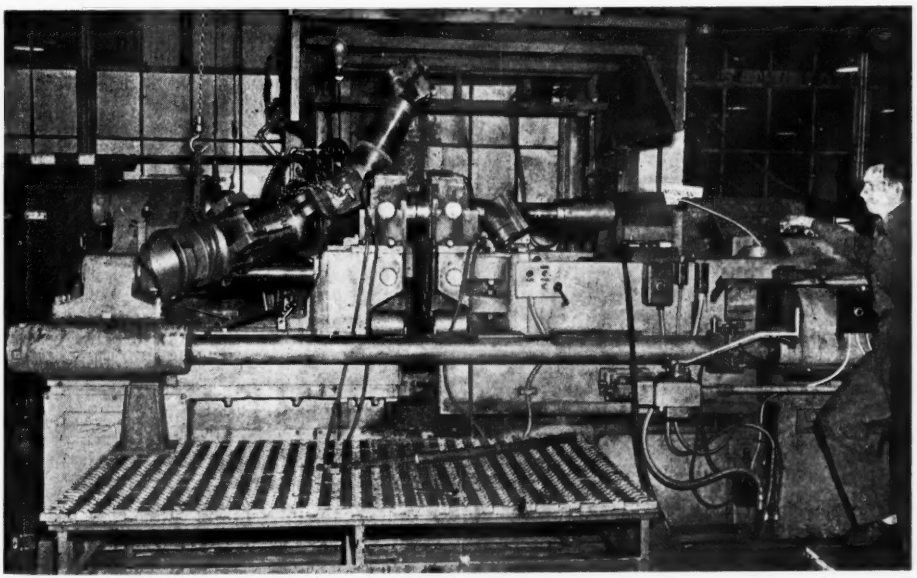


Fig. 20.
Flash-welding undercarriage parts in the U.S.A.

proven as satisfactory as the low carbon weld metal even though the welded assembly is subsequently heat treated to higher physical properties. Unless the assembly is to be heat treated to higher values, the usual practice is to use it in the 'as welded' condition without any normalising or stress relief treatments. Because most aircraft tubing is purchased in the normalised temper, it is welded in that condition. In the case of 4130 or 8630 steels, many assemblies are then used without further treatment. This has been found advisable because normalising for stress relief of the weld zone lowers the yield strength and fatigue resistance of the welded part. The design considerations, due to the heat-affected zone being slightly different from the parent metal for 4130 or 8630 steels, are covered in Army - Navy - Commerce Bulletin ANC-5. This Government Bulletin covers the reduction in design values required by the civil as well as the military services. These design reductions depend on the sequence of welding and heat - treating operations, whether the weld is made by arc, torch, or electric flash, and the shape or geometry of the welded joint.

"The usual practice is not actually to make hardness tests of the welds on production parts but to rely on the great volume of existing data to indicate what the safe design allowables are. Checks are then made for the inspection of the parent metal somewhat away from the weld to determine the heat-treatment results or temper of the assembly. Thus no minimum hardness or strength value is set up for the purpose of inspection of the weld metal itself.

"Depending on the sizes and wall gauges of the components, in general, the following tempers or physical conditions of 4130 or 8630 steels are considered standard: —

Normalised—95,000 lb. sq. in. ult. tens. strength.

Normalised—90,000 lb. sq. in. ult. tens. strength in heavy gauges.

Heat treated to 125,000 to 145,000 lb. sq. in. ult. tens. strength.

Heat treated to 150,000 to 170,000 lb. sq. in. ult. tens. strength.

Heat treated to 180,000 to 200,000 lb. sq. in. ult. tens. strength."

It also stated that this Company uses an allowable stress factor of .95 for flash-welded structures, giving a small additional safety margin, and requires every important, or "Class I," structure to be proof-tested.

The use of steel forgings in this manner results in very high prototype costs. There is no other course to adopt than to machine the parts all over from rough hand forgings; use is made of profile copying machines of the Keller or Cincinnatti Hydrotel type, but in spite of this the costs are very high. As an example, a single undercarriage leg for the B.36 aircraft comprising the shock absorber, axle and upper trunnion only, costs about $250,000 (£62,500), the whole landing gear without wheels and tyres and retraction gear costing about $700,000 (£175,000).

It is evident that when there is a sufficiently large production run to enable the large tool and die cost to be amortised, this American method is of great interest from the point of view of weight and speed of production. As for the cost itself, this obviously decreases with an increase in quantity. For example, the Skymaster undercarriage leg alone, less wheels and radius rods, costs about £750 compared with about £2,000 for an equivalent prototype leg.

2.4.2.1. *Flash welding.*

As already indicated, flash welding can be used to join tubes to forgings to avoid excessive length in the forgings themselves. This process was applied towards the end of the war by the Germans in the production of remarkably cheap undercarriages for the F.W.190, although in this case to obtain the maximum production many lightening machining operations were omitted.

Another variation of the process has been developed in the U.S.A. by the Menasco Company and is known as "pressure welding." In this case the heat is provided by a ring of gas jets taking the place of the electric arc, although the set-up, pressure, and so on, are as for flash welding.

2.4.2.2. *Tube manipulation.*

Another process made use of in the U.S.A. to facilitate undercarriage production is tube manipulation. The Bendix Company of South Bend, Indiana, uses the Bendix-Denvey process to produce parts of the various shapes and forms, as illustrated in Fig. 21.

This process is most useful in producing strut or bracing members for undercarriage frames, radius rods, stays, and so on., with the optimum shape, thickened ends for end fittings, and so on.

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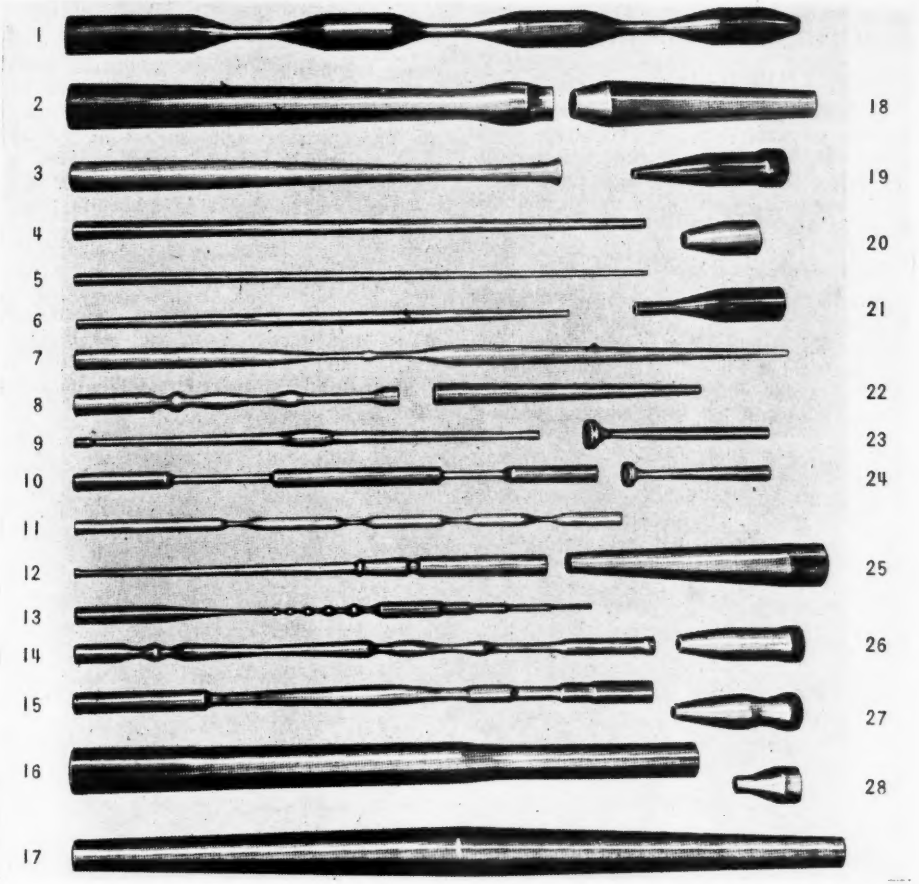


Fig. 21.
The Bendix-Denvey tube manipulation process.

3. RETRACTION REQUIREMENTS.

It becomes more and more difficult to stow the undercarriage into the modern wing.

The laminar flow wing is too thin to contain the wheel and tyre—even with the use of extreme high pressures and tyres of narrow width; in addition, the fuselage is often so full of jet pipes, engine components and so on, that there is scarcely room for the wheel here either. Furthermore, the introduction of the swept-back wing increases the severity of the problem, on the one hand because of the obliquity of the spars and, on the other hand, the position of the centre of gravity in relation to them.

We cannot therefore suggest a general solution to a problem with so many particular aspects. It will suffice to illustrate some recent solutions which have been designed or built and which in certain cases may be of value to the aeroplane designer.

3.1. HINGED WHEELS.

3.1.1. *Morane.*

Figure 22 illustrates a system where prior to retraction the wheel is hinged about a longitudinal axis until it lies at right angles to the leg axis, then retracting into a vertical trough in the fuselage, the leg only remaining in the wing. This system has been developed

by the Morane Company and used on several hundred aircraft with excellent results.

3.1.2. *S.E.*1010.

Figure 23 shows a system used on the S.E.1010 aircraft where the wheel turns round about the shock absorber axis during retraction backward, to lie flat in the wing.

This system is well known but is included here for record.

3.1.3. *Tandem wheels.*

A tandem layout shown in Fig. 24 has been studied for an aircraft of about 25 tons. In our opinion it is much too complicated, but it is not without interest. It has the advantage of keeping the wheels parallel to the wing axis during retraction, thus reducing air drag.

3.2. CONTRACTION OF SHOCK ABSORBER TRAVEL.

An interesting and useful device is the shortening of the undercarriage by contracting its travel during retraction, thus reducing the undercarriage well dimensions. While this was probably first done on a Caudron aircraft in 1938, large numbers of Meteor aircraft with this device have been produced in England.

3.2.1. *Hydraulic solutions.*

The Caudron 710 machine, referred to above, had shock absorbers, the fluid in which could be by-passed into bottles or accumulators during retraction, a cable closing up the undercarriage itself. In

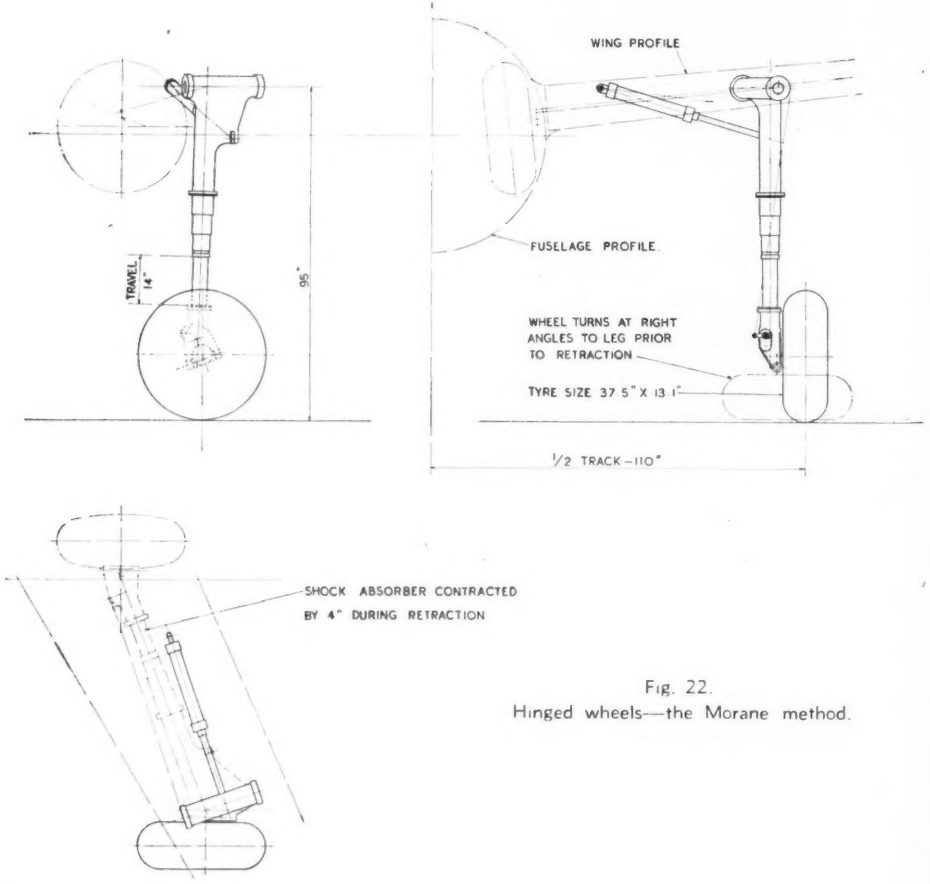

TRAVEL 14"
95°
WING PROFILE
FUSELAGE PROFILE
WHEEL TURNS AT RIGHT ANGLES TO LEG PRIOR TO RETRACTION
TYRE SIZE 37·5" X 13·1"
½ TRACK – 110"
SHOCK ABSORBER CONTRACTED BY 4" DURING RETRACTION

Fig. 22.
Hinged wheels—the Morane method.

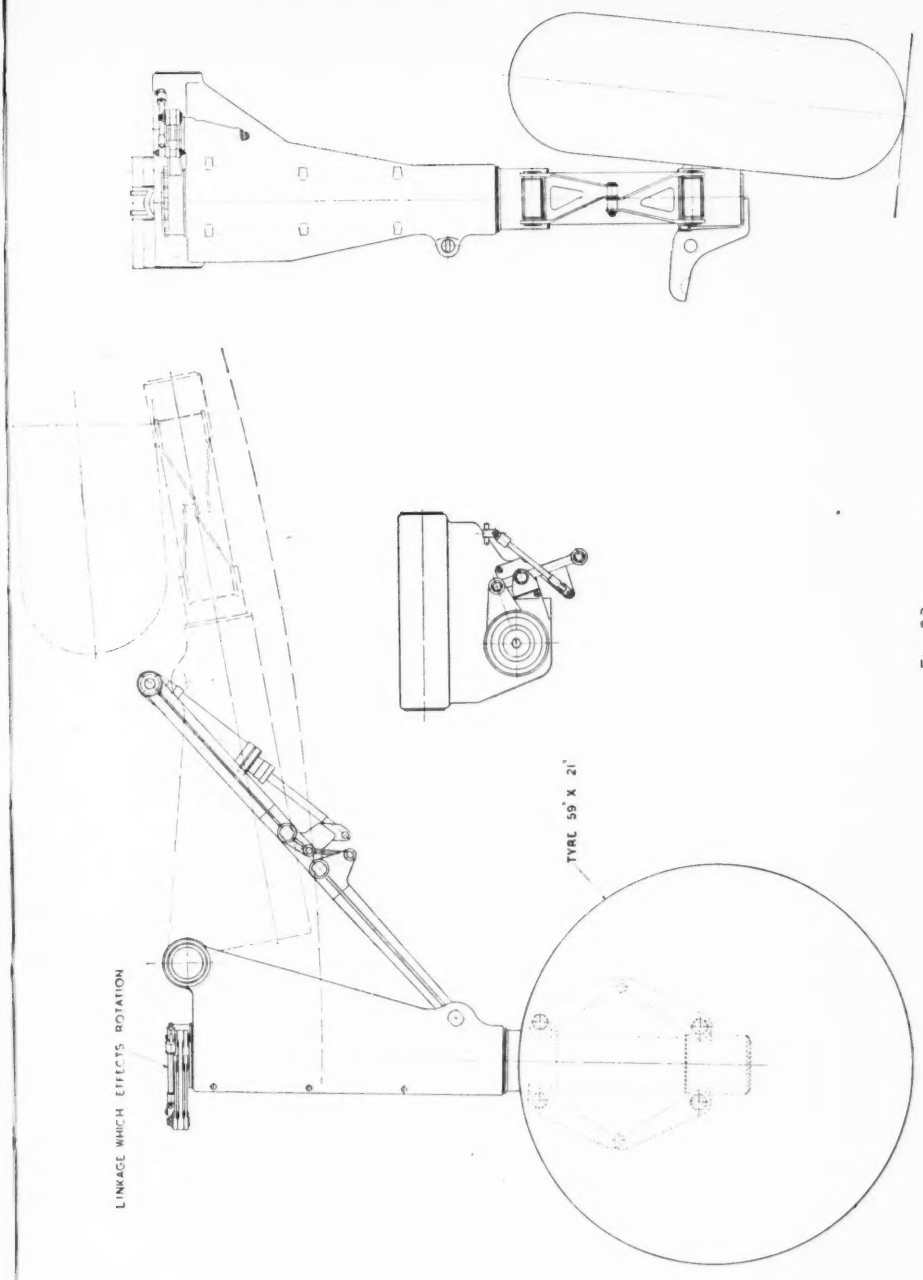
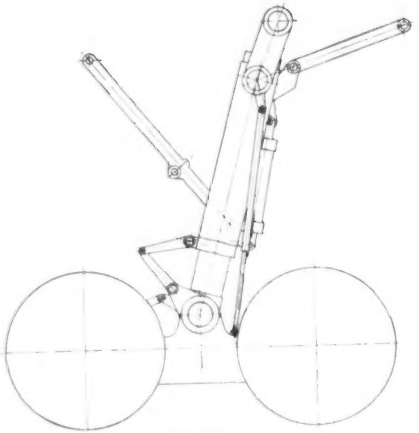
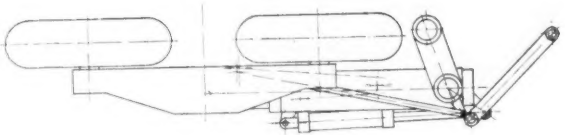


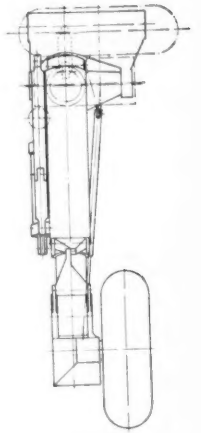
Fig. 23.
Hinged wheels—the S.E.1010 undercarriage.



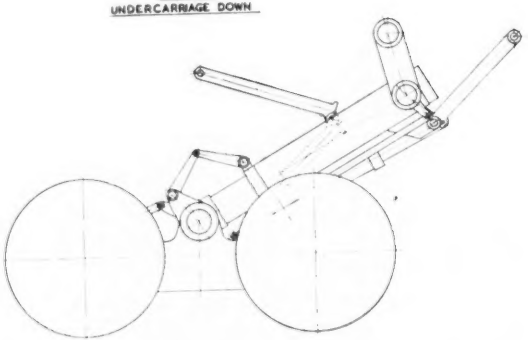
SIDE VIEW
UNDERCARRIAGE DOWN



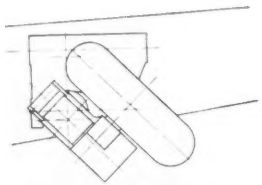
SIDE VIEW
RETRACTED



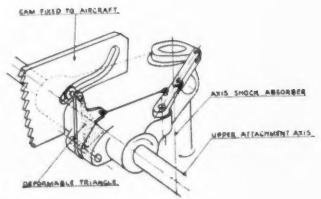
ELEVATION



VIEW RETRACTING



ELEVATION — RETRACTING
WHEEL BOGIE TURNING DUE TO CAM



PERSPECTIVE VIEW OF CAM MECHANISM

Fig. 24
A tandem wheel bogie undercarriage

common with all solutions of this type, the shock absorber relies on a hydraulic locking valve to keep it extended for landing and taxying, something we accept only when forced to do so by circumstances.

Fig. 25 shows a modern design on the same system for the Dassault M.D.161.

3.2.2. *Mechanical solution.*

Where sufficient length is available a telescopic mounting for the undercarriage may be devised with a mechanical lock replacing the hydraulic lock of the hydraulic method, but the loads in the lock due to landing will be high.

With articulated designs, as on the Meteor, a mounting may be chosen for the shock absorber so that the required contracting motion of the fork and wheel is obtained without additional complication. This, of course, is a valuable simplification if the articulated layout is acceptable.

3.3. TANDEM UNDERCARRIAGES.

Brief mention should be made of the recent interest in tandem undercarriages in the United States, a development which recalls particularly the original Messier aeroplane of 1931, which had two wheels mounted in tandem in the fuselage with outrigger skids for slow speed stability. This is precisely what has been done recently by the Glen Martin Company, except that the skids are replaced by small wheels. Apart from the interest of such a layout for removing the undercarriages from the wings, it has the particular feature of making possible much heavier braking than is possible now, by using a braked front wheel.

3.4. SKIDS.

There is no doubt that the skid undercarriage is going to come in some form and for some operational types of aircraft, particularly naval aircraft. It is too early to say exactly on what lines this may develop but the German Me.163 and Ar.234 are interesting pointers.

4. RUNWAY EQUIPMENT.

It is not at all ridiculous to say that runway equipment constitutes an important part of the landing gear. More and more we are striving to lighten and, if possible, eliminate the undercarriage, albeit at considerable expense in providing runway equipment to take its place.

Apart from the devices mentioned below the runway itself can be improved from the operational point of view:—

(i) by an increase in length;
(ii) by increasing its capacity to support greater wheel loads.

This last point involves not only the strength of the concrete itself, but the tilting of the concrete slabs when loaded at the edge, requiring mechanical connection of the adjoining slabs.

As regards length, the consideration put forward in paragraph 2.1.2 (Take-off and landing) lead to the conclusion that for long distance trans-continental operation, the optimum take-off angle of attack may not be obtainable to avoid excessive length of the undercarriage, this leading to the construction of runways of exceptional length.

To date, experience has been limited to maximum tyre pressures of 150 lb. sq. in. on runways. Tyre pressures up to 300 lb. sq. in. have been tested experimentally in the U.S.A., which seems to point to the ultimate possibility of all-metal runways.

4.1. THE ELECTRIC TROLLEY (the Westinghouse "Electropult").

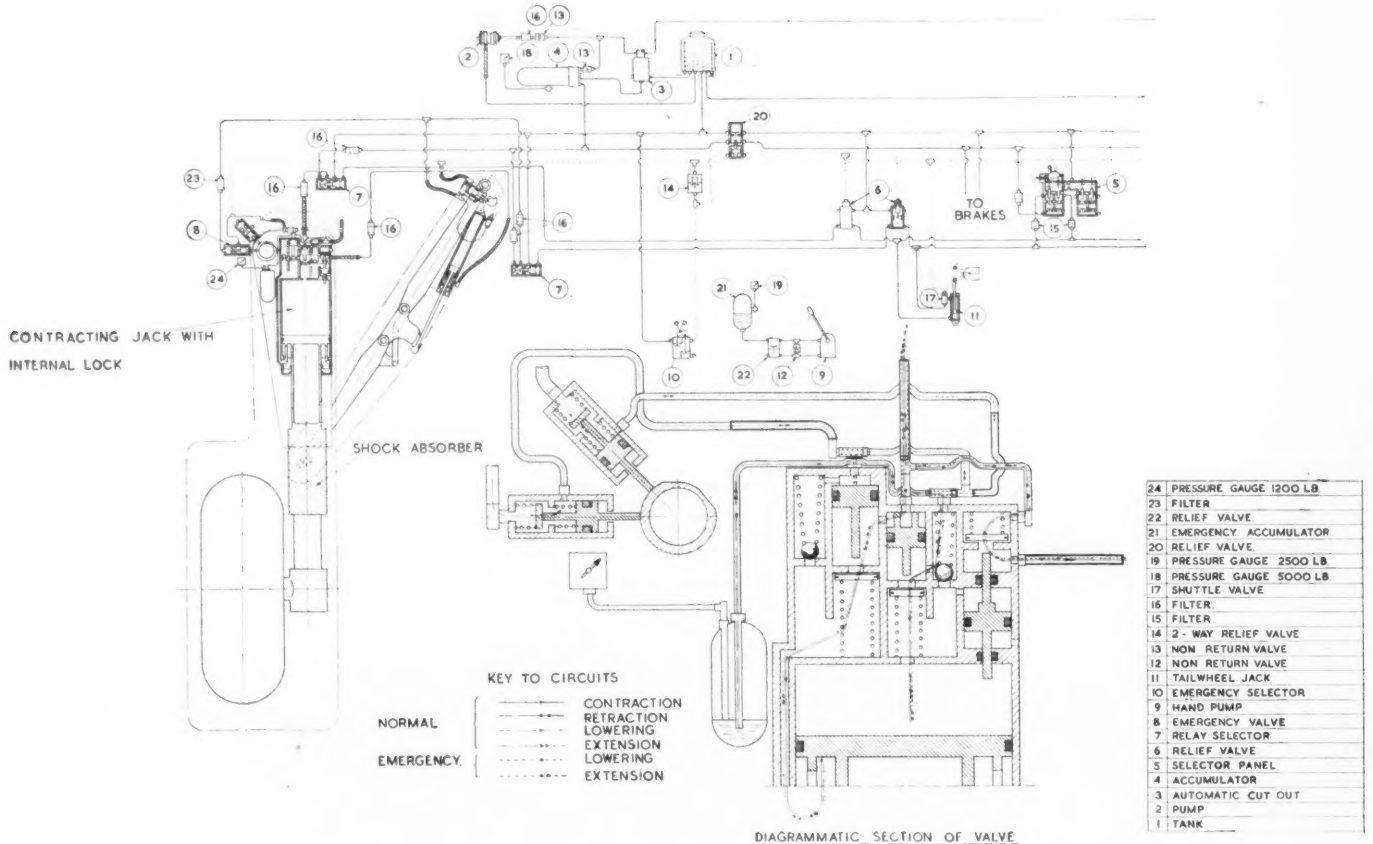
The American Westinghouse Company has developed a take-off trolley which consists of a type of electric motor which is unwrapped along the runway for a length of 450 yards. The "stator" consists of a trolley which moves axially along and above the "motor," being fitted with wheels which run on rails. The rails are sunk in the ground and the trolley barely projects above it. The aircraft can be attached to the trolley and released rapidly when the take-off speed is reached, as in a naval catapult; a heavy fighter can be accelerated to 116 m.p.h. in 340 feet.

The power is supplied by an aircraft engine of 1,100 h.p. driving a D.C. generator, which drives a D.C. motor which, in turn, drives an alternator. The latter is coupled to a heavy flywheel to help provide the 12,000 k.w. peak load. The system is of interest because it can be used by commercial aircraft without much modification to them; the attachment of the aircraft to the trolley is rapid and does not require lifting gear.

4.2. THE WHEEL BOGIE.

The auxiliary wheel bogie has been used successfully in Germany, but in the shape of a light and detachable pair of wheels which are left behind at take-off.

A tandem wheel bogie undercarriage



RENE LUCIEN

Fig. 25.
A hydraulically contracting undercarriage—the M.D. 161.

A hydraulically contracting undercarriage—the M.D. 161.

At the moment, work is in hand on a type of bogie fitted with a steerable nose wheel, and fully radio-controlled, and which can be used as a take-off device for a fighter (landing being on a skid) or for a guided missile.

The French Michelin Company is developing high speed tyres especially for such a bogie.

5. CONCLUSION.

If it is true to say that the extension of air transport throughout the world brings about a degree of standardisation of airframe components and a unification of stressing requirements for the airframe itself, this is even more true for the undercarriage.

The undercarriage is, in fact, an essential intermediary between the aeroplane and catastrophe: although it is put to use at infrequent intervals, the forces developed are appreciable and difficult enough to keep under control. It is necessary therefore to select a common approach and to make the greatest use of standardised elements.

The work of I.C.A.O. has produced a set of conditions for the stressing of the landing gear; now these, differing as they do from the latest national requirements, make additional mathematical verification necessary.

The French Service Technique, to whom we have made the suggestion, is about to revise its requirements, using I.C.A.O. requirements as a basis, and tightening up only when particular circumstances make it vital.

We wish that this example could be followed in other countries; it would be the first step towards the international agreement that will one day dominate our industry.

Furthermore, and as regards the standardisation of the elements, we believe that, pending a comprehensive organisation of international standards, immediate action on an international basis should be taken to standardise five or six tyres, from those which are the most up to date and popular (starting for example with the Dakota and Constellation), each tyre maker making these sizes and overcoming any chauvinistic leanings in the general interest.

We must try to standardise throughout the world fluids, pipe sizes, pipe fittings, hydraulic pressures and electrical voltages, D.C. and A.C. . . . A decision, even if imperfect, would, if generally adopted, effect large savings of money and eliminate thousands of hours of unserviceability.

We are fully conscious that the paradox of basic units divides us—what we on our hand may say in favour of the metric system is that it is, at least, perfectly defined, while everyone knows that there are several miles, several tons, several gallons.

In conclusion may I express the hope that the new conception of the modern aeroplane will not bring about an excessive complication of the undercarriage, which unfortunately already tends in that direction daily—a complication which means more weight, more cost and less safety of operation.

ACKNOWLEDGMENTS.

Grateful acknowledgments are made to Mr. J. F. Wallace of the Cleveland Pneumatic Tool Company, Mr. O. Johnson of the Bendix Aviation Corporation, and Mr. H. L. Hibbard of the Lockheed Aircraft Corporation for generously providing information on American practice; to Mr. Katz, the Aero Sud-Est, and Chausson Companies; and to the Institute of Aeronautical Sciences, the Society of Automotive Engineers and the Association Francaise des Ingenieurs et Techniciens de l'Aeronautique, for help in obtaining information from their members.

APPENDIX I.

DEFINITION OF FRENCH TORQUE FACTOR (cote de couple) C.

C_f = brake torque per brake.
n = number of brakes per wheel.
F = static load per braked wheel.
r = rolling radius.

Skid torque: C_p.

The tyre-to-ground coefficient of friction is assumed to be equal to 0.65. Evidently therefore:

$$C_p = 0.65 \times F \times r.$$

Torque factor: C.

$$C = \frac{\text{Brake torque per wheel}}{\text{Skid torque per wheel}} = \frac{n \times C_f}{C_p}$$

Ground drag for a torque factor of $C = T$.

$$T = \frac{n \times C_f}{r} = \frac{C \times C_p}{r} = \frac{C \times 0.65 \times F \times r}{r}$$
$$= 0.65 \times C \times F.$$

NOTE:

(i) For a tricycle aircraft where braking is not limited by over-turning consideration, the torque factor may equal, or even exceed, unity.

(ii) For tail wheel aircraft the torque factor will usually not exceed 0.5-0.6, due to the risk of over-turning.

(iii) The nominal British requirement of a deceleration of 10 ft. sec.-sec. (0.31g) corresponds to a torque factor of .5 approximately.

(iv) The American "ground coefficients" of 0.3 (and 0.55 in the emergency case) correspond to torque factors of 0.5 approximately (and 0.85).

APPENDIX II.

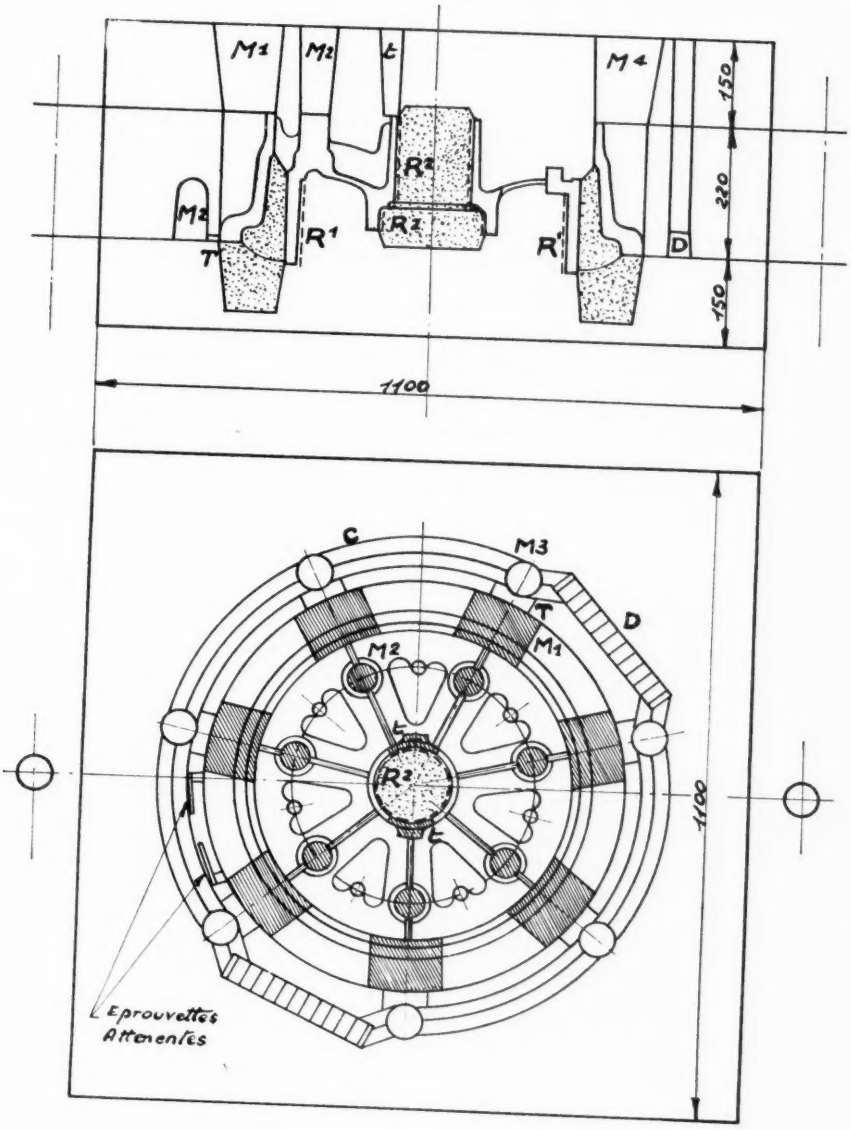
TYPICAL FOUNDRY SPECIFICATION FOR FRENCH LIGHT ALLOY CASTING

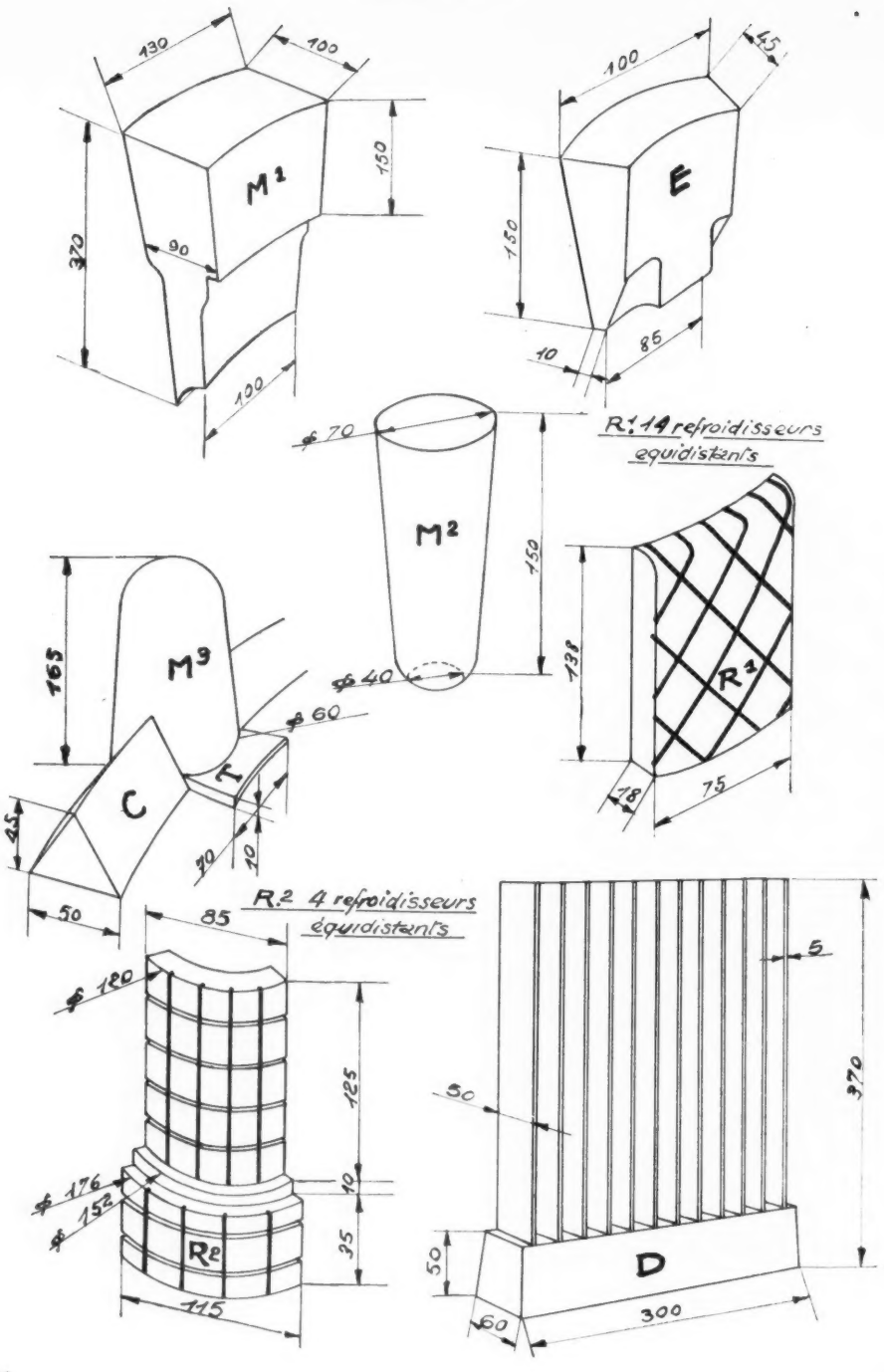
F I C H E D E F O N D E R I E

D E P I E C E E N A L L I A G E D E M A G N E S I U M

I.- a)	DESIGNATION PRECISE DE LA PIECE	: Demi-roue 22,5 n° 237.639-640. Modele 237.639-640. (Fiche commune).
b)	DESTINATION	: Avions Breguet 761 et M.B. 161.
c)	CATEGORIE	: C.
II.-	FONDEUR - Raison Sociale	: MESSIER - ARUDY.
	Siège Social	: 6, Avenue Raymond Poincaré PARIS - 16°
	Usine	: ARUDY (Basses-Pyrénées)
	CONSTRUCTEUR	: MESSIER - MONTROUGE.
III.-	ALLIAGE UTILISE	: G-A4Z3.
IV.-	MODE DE MOULAGE	
a)	Modèle	: Bois.
b)	Boite	: Bois.
c)	Procédé de moulage	: Main.
d)	Nature du moule	: Sable vert : Soufre 3-5 % Acide borique 0,25 % Bentonite 5% Eau 3,5 à 4,5 % Sable à 5-7 % argile : reste.
e)	Nature du noyau	: Sable précédent etuvé.
f)	Séchage	: 140-150°.
V.-	FUSION.	
	Fours	: Mazout, creusets en fer de 50 Kgs.
	Flux	: MESSIER.
	Température de coulée de la pièce	: 745-730°.
VI.-	TRAITEMENTS THERMIQUES	: Sans objet.
VII.-	FORME DU MOULE	: Voir croquis page 3 et 4.

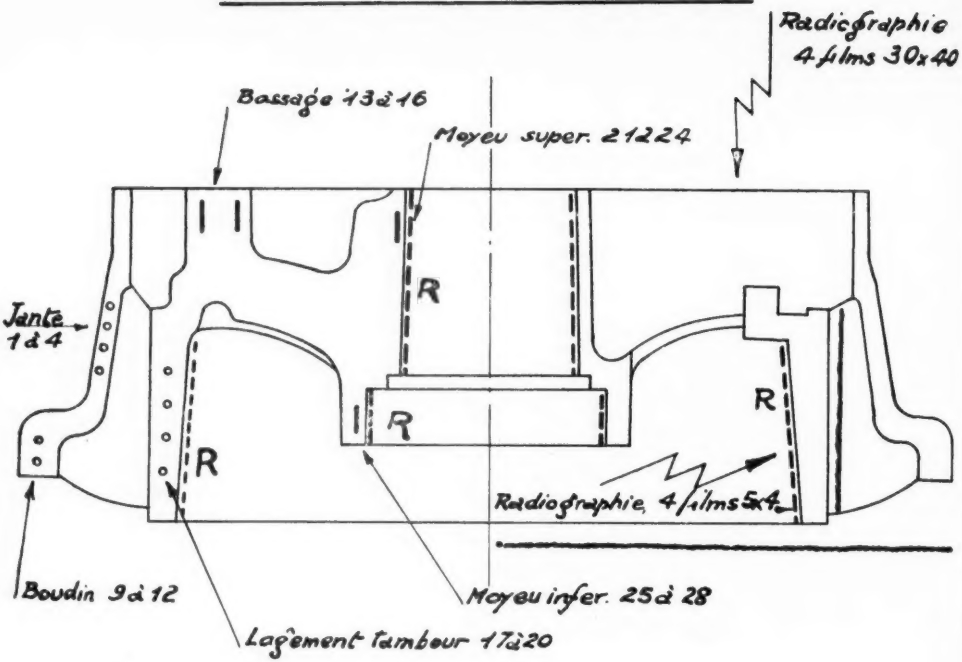
MOULAGE DE LA PIECE

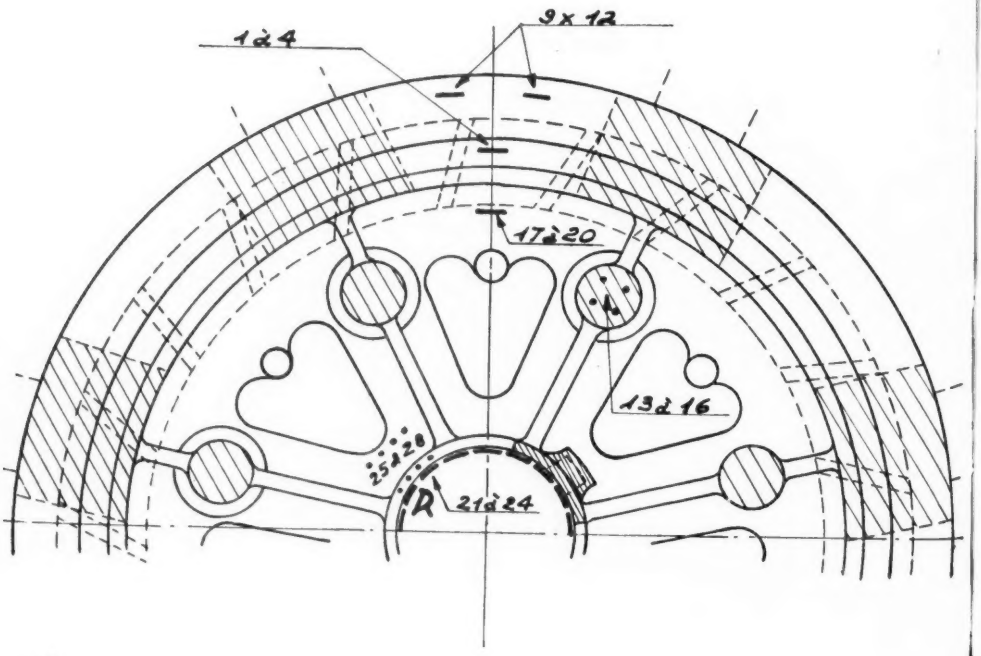



130
100
150
370
90
100
M1
100
45
150
E
10
85
R1 14 refroidisseurs
equidistants
⌀ 70
M2
150
⌀ 40
165
M3
⌀ 60
C
T
45
50
70
10
138
R1
78
75
R2 4 refroidisseurs
équidistants
85
⌀ 120
125
10
⌀ 176
⌀ 152
35
R2
115
5
50
370
50
D
60
300

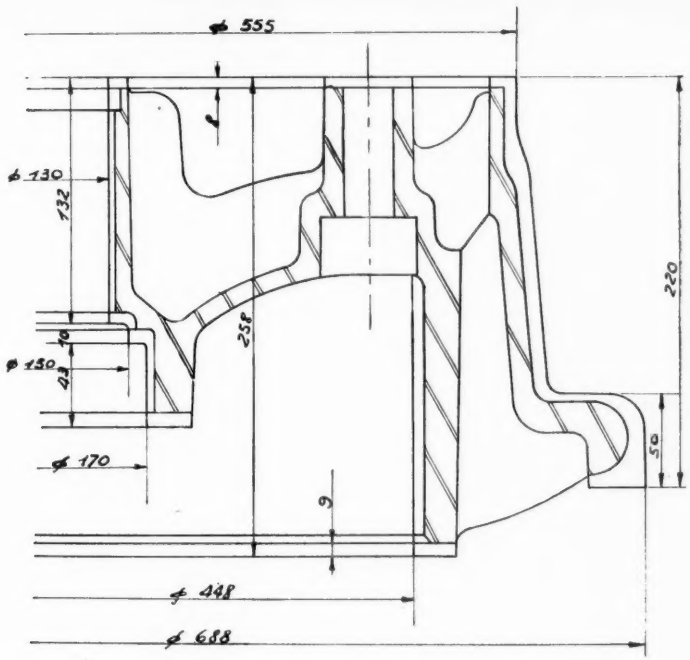
VIII.- CONDITIONS DU CONTROLE EN SERIE	Les numéros des paragraphes renvoient à l'Instruction 520/DTI/STA/SPA du 11-1-46.
A. LOTISSEMENT	: Artificiel 10-15-25-35-25-50-50 etc. d'après § 4-123-4-b. 1 pièce par coulée (à 2 poches).
B. ESSAIS CHIMIQUES	
a) Prélèvements	: Ebauches pour spectrographie coulées à part.
b) Pourcentage	: Intégré dans contrôle métallurgique général : 1 coulée sur 3 analysée.
c) Résultats à obtenir	: Conformes à § 4-113.
d) Sanctions	: Contre-essais 2 coulées sur 3. Hors tolérances Al et Zn : rajuster Hors tolérances Si - Cu - Fe et Mn < 0,15 rebuts.
C. ESSAIS MECANIQUES	
a) Essais sur éprouvettes séparées	: Intégré dans contrôle métallurgique courant. Standard MESSIER MA-T4. Hors tolérances : essai individuel sur chaque pièce.
b) Essais sur éprouvettes attenantes.	
1. Prélèvements	: 2 barettes suivant croquis page 3.
2. Pourcentage	: Individuel.
3. Nature	: 2 tractions micro-machine Chévenard, norme MESSIER MM-T2 par pièce contrôlée.
4. Résultats à obtenir	: Minima conformes à § 2-322.
5. Sanctions	: Suivant § 4-122-3.
c) Essais de dissection.	
1. Prélèvements	: Pièce type : complete suivant croquis page 6 (6 zones, 24 éprouvettes). Dissection en cours de série : 3 zones sollicitées logement tambour moyeu inférieur, boudin.
2. Pourcentage	: 1 pièce par lot suivant § 4-123-4-b

DISSECTION DE LA PIECE TYPE





SURÉPAISSEURS D'USINAGE



3. Résultats à obtenir : Zones sollicitées : minima § 2-322.

4. Sanctions : Conforme au § 4-123-5.

D. ESSAIS PHYSIQUES

a) Dimensions.

1. Tolérances : Suivant § 4-131-1.
Surépaisseur : croquis page 7.

2. Pourcentage : Suivant § 4-131-2.
Traçage complet : 1 piece par lot.
Si cotes anormales vérification indrviduelle.

b) Santé.

1. Défauts externes : Individuel suivant § 4-133.

2. Défauts internes : Radioscopie : sans objet.
Radiographie : Individuelle suivant croquis page 6.

c) Texture : Suivant § 4-132.
Cassure : éprouvettes attenantes et pièce de dissection.

X.- POIDS

Poids de la pièce munie de tous les appendices : 112 Kgs

Poids de la pièce prête à être livrée : 42,5 Kgs

DISCUSSION

G. H. Dowty (Dowty Equipment Ltd., *Fellow*): He expressed his appreciation of the tribute which Captain Lucien had paid to the development work done in this country during the war years.

An undercarriage layout which had been illustrated had reminded him of a design put forward some years ago in which the wheel had to be turned through 90° and then tilted through 40°. Even then, the wheel would not fit into the appointed place, and the designer seriously suggested that the tyre might be deflated during retraction!

Undercarriage design should not be complicated. Complication meant increased weight and cost and if it were not found possible to use a straightforward and simple design, he considered that the design of the aeroplane itself was fundamentally wrong.

Captain Lucien had confined his remarks on shock absorbers to a particular type which he claimed would meet certain conditions at high taxying speed. His own experience in this country, and which he believed was true of America, was that such additional complication had not been found necessary. The tyre was quite capable of looking after these conditions. Furthermore, the design mentioned by the lecturer would be unsuitable for a nose wheel, where very much higher resistance was required during taxying.

As to which was the best type of shock absorber, he was perhaps treading on delicate ground; but since Captain Lucien was so keen on simplification, he would call attention to a particular type of shock absorber which he was told used "fluid in compression"!

He agreed with Captain Lucien that where rectilinear motion was required, electrical operation was illogical. There was a good argument for the electro-hydraulic system, in that it eliminated the fluid lines in the fuselage, a fact which designers would appreciate.

He disagreed that they could not contemplate a pneumatic pressure of 1,200 to 1,400 lb. per sq. in.; pressures as high as 5,000 lb. per sq. in. were being achieved to-day.

He shared the hope that undercarriage design in general would become simpler.

N. E. Rowe (Controller, Research and Long-Term Development, British European Airways, *Fellow*): Captain Lucien had remarked that the undercarriage was the intermediary between the aeroplane and catastrophe, but he supposed there were those who would say that the undercarriage was the obstacle between the aeroplane and freedom! He did not necessarily share the latter view, but he had heard it said that the final development of the undercarriage would be its elimination; that was a view which he would commend for discussion, and he invited the comments of aircraft designers on the matter. It was something to which they ought to be able to look forward within reasonable time, at least for small aeroplanes.

Standardisation, the need for which had been emphasised in the paper, was a sound aim, especially in relation to such things as the fluid pipe lines, connections, and so on. But he had grave doubts about the standardisation of any major component such as the tyre. It seemed to him that standardisation was excellent in wartime, in order that one should always have the parts available wherever one might be, and in order to be able to reduce production time and costs, and so on. But an enormous amount of standard material would be produced which might have the great disadvantage of discouraging invention. That was something they should consider carefully. There might be other solutions, altogether different from the rubber tyre, to which they had become accustomed over a period of many years; but if they could produce a tyre which would give only a fixed resistance in braking, and so on, they might do harm rather than good.

He had always felt that certain undercarriage stressing requirements were the fault of the aircraft rather than the undercarriage. If they could design aeroplanes which would be simple and easy to land, which gave confidence to the pilot in the knowledge that he could make a good landing under difficult conditions, with side winds, and so on, the undercarriage would have a much easier duty and the stressing requirements could definitely be reduced. He supposed that what they needed most of all was a great deal of statistical information on the loads and stresses that actually occurred in undercarriages; only when they had that information, had built up a real theory and had checked it with results, could they expect to make the best undercarriages, as light as they ought to be—apart from their elimination.

As to the castoring of wheels, his personal opinion was that there was much to be said for it, not only on small aircraft, but also

on larger ones. He would like to hear Captain Lucien's views on the possible reduction of loads by the use of castoring main undercarriage wheels, thus avoiding the side loads which occurred largely in practice nowadays.

While the undercarriage had quite properly become a specialised mechanism, to be dealt with by specialised people in the best way, he urged that the general layout of the undercarriage should be the responsibility of the designer of the aircraft, who knew best what he required his aeroplane to do. He then collaborated and co-operated with the undercarriage designer in order to ensure that the detailed design of the undercarriage was the best he could get to meet his requirements. One would like to hear further views on that suggestion.

He would also like to hear more about the long travel undercarriages to which Captain Lucien had referred, their cost in weight and complication, and so on, because they might be a real factor in solving the problem of landing in difficult conditions of visibility at reasonable rates of descent.

The pre-rotation of wheels seemed to be popular in America and was effected in various ways, such as by flaps moulded to the side walls of the tyres to rotate the wheels at a certain speed. They had concluded during the war that the amount of tyre wear due to starting up and landing was small and that it was not necessary to pre-rotate the wheels. Captain Lucien's views on that would be of value.

He suggested that Captain Lucien might direct his attention to the undercarriage problem of the helicopter, which, he believed, was quite different from that of the normal fixed wing aeroplane. It was very different in taxying; it usually landed lightly, but it might land very heavily. There was also the question of stabilisation on the ground, and that of the absorption of energy when running up the rotor. The solution of that problem might lead to the elimination of tyres altogether, on this type of aircraft.

W. Tye (Air Registration Board, *Fellow*): He supported Captain Lucien's remarks concerning the building up of an international schedule of requirements for landing gears on the basis of systematic testing; in that respect they were very badly off. He also agreed on the need for basing all the national requirements on the international standards in order to avoid an embarrassing situation for the designer in having to check against two separate sets of requirements. In this country they had faced up to the problem to a very large extent. The present British Civil Airworthiness Requirements had adopted to a considerable degree the international requirements as they stood, and in certain small regions they had found it necessary to amplify international requirements. Thus the designer, by conforming with the British requirements, could be sure that he was conforming with the international requirements.

Captain Lucien had put him on the defensive to some extent in expressing his general view of the present international requirements. Admitting the absence of much loading information, he believed they were about the best that could be evolved in the circumstances. So far as the principal stressing cases were concerned, those relating to landing and manœuvring during take-off were, in fact, based on the considerable wartime experience gained in the United States and the United Kingdom. At the early meetings of P.I.C.A.O. it had transpired that, although British and American requirements had formerly been somewhat different, during the war both had thought on much the same lines, and the strength requirements that were being considered in both countries for civil application were very close together. The result was that the international requirements were to a large extent those developed from American and British experience. That experience, as Captain Lucien said, included the bad aeroplanes as well as the good ones; but it seemed in the nature of things that in the early design stages one could not always foresee whether an aeroplane would be good or bad, so that the Airworthiness Authority could not rely on the aeroplane being "good."

Inasmuch as their present civil requirements were drawn on the basis of military experience, they might find that they had overdone it, providing for more strength than was really required for what they hoped would be the less onerous conditions of civil operation. Time alone would prove whether or not that was the case; but if they erred in one direction or the other it was as well, particularly in civil aviation, to have erred on the safe side.

R. S. Stafford (Handley Page Ltd., *Fellow*): Captain Lucien's work had found expression in the undercarriage used on the Halifax aircraft, which had given great satisfaction in

service. Did Captain Lucien consider that the locking of nose wheels was really necessary? In the case of the steerable nose wheel, if locking was not required, it appeared possible for the nose wheel to be free to castor, or steerable without a separate lock control for the pilot—the same as for a motor car—such as the DC-6 and Hermes IV. In this country both the civil and military operators had so far decided against locking.

In his firm they favoured nose wheel movement through a wide range, $\pm 90°$, which met the requirements for ground manhandling of the aircraft as well as for taxying.

That did raise one problem, and that was the gearing between the nose wheel and the pilot's control; one would like to hear Captain Lucien's views as to what were desirable gear ratios.

The all-castoring type undercarriage had been the subject of considerable development work in the United States, and apparently a great saving indeed was possible in aerodrome construction and maintenance costs if a single runway were sufficient. A recent American estimate had indicated that on a seven-year programme 500 million dollars could be saved by using one-way airports, the corresponding estimated cost of modifying all aircraft now in service to have all-castoring undercarriages being 12 million dollars. Those were startling figures, and it became interesting to know what was the weight penalty of that type of undercarriage as applied to transport aircraft, so that an overall assessment could be made of the overall costs of operation. Had Captain Lucien any figures for relative weight of fully-castoring as compared with orthodox aircraft in the weight range 50,000 to 200,000 lb?

It was interesting to note that the French constructors considered the French official braking requirements to be too severe; much the same state of affairs existed here as regards A.R.B. leaflet D.38, issue 1, June, 1947, the point at issue being the amounts of energy to be absorbed for the various cases. Taking, for example, the bag type brake, in the conditions obtaining prior to the introduction of leaflet D.38, the weight of metal absorbing the braking energy in a given case was 74.5 lb., which was taken as 100 per cent., but the existing D.38 requirements, the I.C.A.N. (accelerated stop case), would increase this weight to 174 lb., *i.e.* to 240 per cent. If tropical conditions were assumed, instead of I.C.A.N., there was a further increase, and the respective values became 130 and 300 per cent. It was hoped to establish a more favourable interpretation of the official requirements.

It would be interesting to know the logic behind the selection of 100 m.p.h. as the mean landing speed for all types, as mentioned in the paper, and also the connection between that speed and the use of standard wheels.

A good case had been made by Captain Lucien for the disc brake. What were the relative weights of the disc brake and the well-tried bag brake?

He believed that drag loads for the undercarriage specified by current A.R.B. requirements were unnecessarily high. For example, a landing drag force of 0.8 of the vertical reaction was required, together with a safety factor of 1.5. Some relief was permissible when pre-rotation of the landing wheels was provided, but he questioned whether the high drag loads were backed by acceleration records. Many thousands of Halifax aircraft were flown during the war under unfavourable conditions, involving severe landings. For that aircraft the reserve factor calculated on the current A.R.B. requirements for drag load was only 0.5, and yet there was no record of structural failure attributable to high drag load. He believed the high drag factors imposed now were the result of the bad aeroplane, or perhaps the bad undercarriage, and that the drag force was influenced by shock absorber design. He believed, provided that sufficient overlap were allowed in the shock absorber leg, that factor when measured would be found to be much lower.

Had Captain Lucien any accelerometer records to justify a landing drag force coefficient of 0.8 (the corresponding French factor was 0.75)? He agreed that there was a great need for statistical data on the point. In the larger sizes of aircraft, they could foresee great structure weight saving both on airframe and undercarriage if pre-rotation would reduce landing drag factors appreciably, or if other means were found to justify smaller drag forces.

Professor G. Temple (*Fellow*): The occasion was a happy reminder of days at the R.A.E., when he was instructed in the elements of shimmying by his guide, philosopher and friend, Mr. P. H. Watson; and days spent looking at tail wheels which shimmied violently before inspection, after which they appeared to be inexorably locked.

Captain Lucien had invited the results of British experience with the freely castoring wheel. It was difficult to offer an opinion about the device described without seeing detail drawings, but it did appear to incorporate the merits both of the self-centring device and of the shimmy damper.

Their experience of self-centring devices was that there were two kinds. The first was the "bad kind," in which the resisting torque increased with the angle through which the wheel was turned. That was bad because the device there acted as a spring and did not absorb energy, and therefore, it did not damp or prevent shimmying. Then there was the "good" type, in which the torque which resisted the angular displacement of the wheel had a fairly constant value, so that the wheel would not rotate from the central position unless the side forces due to ground friction caused the torque to exceed the critical value. He referred to that as the good kind because it had so many merits. If properly designed and if the resisting torque produced by the self-centring device were of the right magnitude, it would be sufficient to prevent the initiation of shimmying, while at the same time it would be low enough to allow the wheel to castor if it ran over a bump or depression.

The tail wheel unit designed by Mr. L. E. Cowey, of British Landing Gears Ltd., incorporated some of the better features of the self-centring device and was extremely efficient. He mentioned it because he did not think that that particular device was very widely known.

It seemed, from the cursory description which Captain Lucien had given, that he had a device in which hydraulic single-action dampers might also act as a means of self-centring. Would he give more details?

S. M. Parker (Lockheed Hydraulic Brake Co. Ltd.): Had Captain Lucien's experience with light alloy castings and with welded structures brought him up against the same difficulties as his Company had experienced, namely, that they were dealing with a structure which had a very low factor of safety and they were required to explore the strengths of some of those welded structures and cast parts to factors which were comparable with, or greater than, the factors on the assembly as a whole? Unless the casting or welded part could be isolated, that requirement could lead to very high cost in testing. Had Captain Lucien found that to be a difficulty which outweighed any advantages derived in other directions? It seemed to him that, unless those advantages were appreciable, such as in the direction of weight, the extra cost represented a serious snag.

He did not think there was unanimity as to the best way in which to effect the emergency operation of undercarriages; what was the French practice in that particular matter?

The Messier Company, both in England and in France, so far as he could judge, had used internal locks for some time, whereas English practice on the whole had been in the direction of external locks. His own feelings in the matter were in the direction of having no locks. Would Captain Lucien give his views on the use of over-centre or on-centre mechanisms, suitably held by springs or toggles, or something of that kind?

Were the two stressing figures given in Fig. 15 paper figures? The one on the right obviously was calculated; was the other also calculated, and was Captain Lucien quite sure that the actual strength of the undercarriage was not appreciably higher than it indicated? It had been his own experience that on the whole, while undercarriages had weak spots, when they had been dealt with, the strength of the structures as a whole was often considerably greater than that calculated.

C. G. A. Woodford (The English Electric Co. Ltd., *Assoc. Fellow*): The point which had struck him particularly about Captain Lucien's paper was that in the majority of aeroplanes the landing gear had to be actuated, and he was sorry that more had not been stated about methods of actuating landing gear other than the old-fashioned method of hydraulics, beyond stating that there was much scope for electro-hydraulics. But only one aspect of that had been dealt with, and that was by adding solenoid- or electro-operated valves to the mechanism of the system. He believed it would be better to supply the power electrically to hydraulic pumps, which would also save a lot of the fluid lines and would give the aeroplane the advantage of a better utilisation of the total power used for the auxiliary services. If the power originated in electricity, that which was available for lifting the undercarriage after take-off was also available for de-icing, especially for tail units, and so on,

in flight, which was not the case with the fluid system.

He agreed that the motor-operated valve was a much better proposition than the solenoid-operated valve, and examples of the former were under development.

Actuators had now been designed and were coming into use in some of the important types of new aircraft—and particularly the replacement of one air liner which he believed was sold in appreciable numbers in dollar areas of the world—in which the undercarriage actuator would be common to the main legs and the nose leg. In the matter of potential standardisation, the main motor driving the actuator could be of interchangeable type, D.C. or A.C. Furthermore, the emergency operation agreed to be embodied in the actuator comprised a small electric motor operated from a separate supply from the accumulator of the aircraft, so that it was possible to ensure driving the undercarriage into the down-lock position. That represented a marked advance in emergency operation which would not be applicable to any form of hydraulic operation.

The power/weight ratio of those motors had now reached a high level.

Mr. Dowty had described as illogical the application of the high-speed electric motor to the operation of landing gear. He did not think it any more illogical than the application of a 10,000 r.p.m. turbine to the driving of a propeller.

W. E. W. Petter (English Electric Co. Ltd., *Fellow*) *contributed*: It was interesting to note how the international implications of aviation so frequently emerged. He wished to comment on the following:

(1) The suggestion that the main wheels of the tricycle undercarriage should be moved farther aft allowing the nose wheel to take a substantial portion of the weight, assuming the aircraft designer could find means of varying effective incidence while allowing the fuselage to remain horizontal.

Did Captain Lucien anticipate that the problem of braking the nose wheel could be satisfactorily solved?

(2) It was agreed that stressing cases had too frequently been severely increased as a result of local failures not necessarily of wide application. There was no doubt that systematic experiments varying a single factor only should be used for determining stressing laws.

(3) The remarks about materials and the manufacturing technique were most interesting. The British designer, however, tended to regard with scepticism the use of welded heat-treated assemblies of forgings and tubes as on the American lines, more especially if stress figures in the finished article of 150,000 lb. per sq. in. or more were envisaged.

It was generally felt in this country that, although such figures might be achieved under conditions of expert welding and supervision, they could not be relied upon under conditions of large-scale production, and there was some evidence to support this view.

The light alloy forging in the high strength aluminium alloys offered a most attractive material for large, highly stressed parts, and, with careful design, it was possible to use hand forgings for small quantities without unreasonable delay or excessive machining and cost. Parts made in this way appeared to be very reliable. More recently the use of high strength steel castings had appeared attractive for certain parts since they were comparatively cheap to develop, and thereafter should not be subject to the same degree of variation as welded parts.

(4) It was felt that the suggestion contained in the concluding remarks that tyres should be standardised to five or six sizes was somewhat premature and would remain so until tyre pressures for different types of aircraft had been more accurately determined than they had been to-day.

P. V. Hoare (Ministry of Supply, *Fellow*) *contributed*: He would like to know how the braking effort was distributed between the main and nose wheels. Although the desirable condition was to land equally on all three wheels and have the weight progressively lowered on to the wheels as the aerodynamic lift decreased, he thought this was difficult to achieve and the more likely condition was a slight pitching, producing a fluctuating load on the nose wheel. In these circumstances equal braking on all the wheels might lead to skidding of the nose wheel with risk of damage to the tyre, as the weight on it was temporarily relieved.

Perhaps this could be overcome by using the undercarriage travel to control the braking and thus interpret the varying reaction in terms of brake torque; a response device would be used to smooth out any rapid

changes of reaction such as occurred in a bounce landing.

Pre-rotation of the landing wheels appeared to be closely coupled with landing technique because if the pilot applied his brakes immediately before touch down (which had frequently happened in Service aircraft) then all the benefit of pre-rotation was lost. To retain the value of such a device it would be an advantage to prevent brake application when the undercarriage was extended with no weight on the wheel; reaction controlled braking would satisfy this condition.

Captain Lucien mentioned the need for a separate system to ensure that braking would always be available. Did he consider it possible to use the potential energy of the aeroplane for this purpose? When they had the whole weight of the aeroplane moving through the travel of the undercarriage and forming an unfailing source of energy, it would seem reasonable to tap some of this energy for use in the emergency brake system.

G. Orloff (British Messier Ltd., *Assoc. Fellow*) *contributed*: Until recently in this country it had not been common practice to specify the energy of landing nor to give the fraction of this energy with which brakes must deal.

This had meant, in the past, that some aircraft had been fitted with brakes of inadequate capacity, but it was interesting to note that aircraft firms were becoming more conscious of the importance of this matter at this time.

In other countries where wheels and brakes had been more or less standardised, it had been usual for a number of years to specify that the brake should be capable of absorbing a particular amount of energy, which had usually been arrived at by calculating the energy corresponding to the stalling speed of the aircraft, since this was approximately the speed at which the brakes were applied.

The energy absorption factor had varied in the different countries, but for the tricycle aircraft a figure of 90 to 100 per cent. was now generally accepted.

He compared the amounts of energy which were specified in America and in this country by the A.R.B. British practice, since it was based on 1.1 × stalling speed, gave a specified energy of 121 per cent. of the energy corresponding to the stalling speed itself whereas the latest American practice used only 96 per cent. of that energy. Since the worst stop in the schedule of tests on which the brake designer had to calculate his brakes in England was at 150 per cent. energy and in America at 125 per cent. energy, the comparison showed the British requirement to be 50 per cent. worse than the American, a situation which would obviously penalise British civil aircraft in the future.

BRAKE ENERGY.
ASSUME TRUE K.E. $= \frac{W.v_s^2}{2g} = 100\%$
A.R.B. PRACTICE (LEAFLET D38) SPECIFIED K.E. $= \frac{W(1{\cdot}1v_s)^2}{2g} = 121\%$ WORST STOP ON TEST IS AT 1·5 X SPECIFIED K.E. $= 181{\cdot}5\%$
U.S. PRACTICE (AN-B-2) SPECIFIED K.E. $= 96\%$ WORST STOP ON TEST IS AT 1·25 X SPECIFIED K.E. $= 120\%$
RATIO $\frac{\text{A.R.B.}}{\text{U.S.}} = \frac{181{\cdot}5}{120} = 1{\cdot}51$

Assuming the stalling speed of the aircraft to be 100 m.p.h. the figures given by Mr. Lucien as representative of latest French practice gave an energy virtually identical with American practice.

These remarks might help to explain why some of the new British civil aircraft were going to have heavy brakes.

A. E. Clarke (Blind Landing Experimental Unit, *Graduate*) *contributed*: In order to assess the weight penalty of undercarriages, would Captain Lucien give average figures for the percentage of aircraft weight represented by:

(i) Conventional undercarriage.
(ii) Tricycle undercarriage.
(iii) Tricycle long travel undercarriage.
(iv) Tricycle Maclaren undercarriage.

R. H. Chaplin (Hawker Aircraft Ltd. *Fellow*) *contributed*: In mentioning the influence of factors which had changed since 1940, Captain Lucien did not include the catering for much higher vertical velocity of

descent, namely, an increase to as much as 16 f.p.s. against 10 f.p.s. as formerly, involving the employment of a shock absorber of more than $2\frac{1}{2}$ times the capacity and an increase in stroke of the same order.

In addition to the static and dynamic stability of a nose wheel which the lecturer had mentioned in connection with behaviour on the ground, aerodynamic stability should also be considered. It was an interesting fact that a normal freely-castoring nose wheel was aerodynamically unstable and would swing into an asymmetrical position after take-off, unless some provision was made against it. He was surprised to learn that this had not been properly appreciated on a certain modern design and led to irritating trouble and delay in early prototype flights. Still more surprising was the fact that shimmy was not yet sufficiently understood to guarantee against it on a new design. Here again, he knew of a recent case where initial trials of a new aircraft were delayed through this cause.

He agreed that the introduction of the tricycle undercarriage had aggravated the problem of braking. Although this layout permitted much higher brake torques, this was of little value because it was not possible to produce those higher torques. Moreover, he did not think they would get much assistance from aerodynamic braking. They made a very approximate calculation and found that to provide a tricycle fighter with drag to equal that of the tail wheel fighter in its tail down attitude after touch down, required the addition of some 20 sq. ft. of air brake area. This was not a practicable proposition.

He had not realised there was a real difficulty in obtaining reasonable taxying performance. He would much appreciate the views of British manufacturers on landing struts.

He endorsed the lecturer's suspicion when he referred to the origin of new requirements and said a fault of a particular aircraft had been responsible for penalising other types of aircraft. He went farther and was suspicious that increases in certain requirements had been put through because of shortcomings with respect to some other requirement. He had in mind the recent increases in vertical velocity of descent which had been considered necessary as a result of failures which could be attributed to detail strength defects, bad shock absorber characteristics or imperfect functioning of the shock absorber strut due to friction.

On the question of materials for use in landing gears, he could speak from experience about the satisfactory use of steel castings. These were made for his company by Hadfield's of Sheffield and were gravity castings as against centrifugal castings, which he believed were the speciality of David Brown Ltd., mentioned by the lecturer. The castings they used provided the pivot for the top of a landing strut. The complete reliability which they experienced led them to use a steel casting for a centre section spar, again with complete reliability, on hundreds of aircraft.

He presumed the two upward reaching arms of the Heinkel undercarriage on Fig. 17 were of tubular cross section and made from half pressings in thick plate, welded along a centre line. When he was in Germany he saw the same method used on a Dornier landing strut for the construction of a wheel half fork, and it seemed a very efficient structure.

He regretted that they could not discuss fully the potentialities of the skid undercarriage. Apart from the naval application envisaged by the lecturer, there seemed plenty of scope in the civil field, where its use in conjunction with an accelerator trolley for take-off would not only contribute directly to the increase of payload, but also indirectly in producing a cleaner aeroplane.

CAPTAIN LUCIEN'S REPLY.

Mr. Dowty: He was glad that Mr. Dowty and he thought along the same lines in regard to undercarriage complication. Experience and good sense had led undercarriage makers to prefer certain simple solutions to be used in preference at all times. Aircraft constructors should use these solutions not only so that their undercarriages were robust and easy to maintain but also because of the saving in weight which resulted. As an example, an aircraft constructor gave them an undercarriage to do where the attachment points had already been fixed so that a simple mechanism was impossible; as a result the percentage weight of the undercarriage was nearer 10 per cent. than the usual 5 per cent. The effect of such an excess weight on the payload of an aircraft was obviously serious.

He was not entirely of the same opinion as Mr. Dowty about shock absorbers with

dual regulation, bearing in mind, however, that none of the experimental solutions proposed in France had yet been fully developed. He believed that, in spite of the tyre, the shock absorber might undergo during taxying accelerations in excess of those generated during landing. High momentary stresses might be transmitted to the airframe, stresses which, while they might not actually be felt by the pilot or crew, might cause serious loads on the airframe.

Accelerometer tests insofar as they had been made would verify those statements. On the other hand, there were other ways of tackling the problem which might be of use. With the use of wheels in tandem, forming a bogey, it was obvious that as one wheel rode over an irregularity in the ground, the shock absorber movement was only half that of one wheel because of the lever effect. It was well known on heavy road vehicles that articulated wheels of this type noticeably improved the riding characteristics and it was thought that a similar result would occur on an aircraft. Another solution applicable to undercarriages of the type used on the Miles Aerovan, where the wheels were carried on levers projecting from the fuselage, was to couple the two levers by a torsion tube with a single central shock absorber. Motion of the two wheels together on landing was controlled in the ordinary way by the shock absorber, but when one wheel lifted as it passed over an irregularity in the ground, the torsion tube was twisted and the shock absorber underwent only half the deflection that would occur if both wheels moved. In addition, the torsion tube could act in the manner of a torsion bar stabiliser used on vehicles to increase roll stiffness.

It was true that the problem of the nose wheel was the converse to that of the main wheel, and the shock absorber must be capable of absorbing the energy generated when the aircraft pitched forward as the brakes were applied. In this case they had under development a system where the shock absorber regulator was adjusted automatically when the brakes were applied, but this development had not yet been tested. On the other hand, the hydraulic inter-connection achieved in 1933 on the tandem undercarriage of the experimental Messier aircraft gave excellent results from this point of view.

Obviously he could give no information on the subject of liquid springs to Mr. Dowty who was already expert on this question; but he hoped that at some future occasion he would explain to him how he had solved the problem of the thermal contraction of the fluid at low temperature.

Mr. Dowty's remarks about an air compressor running at 5,000 lb./sq. in. were most interesting and he congratulated him on results, the excellence of which he could fully appreciate as a result of the work Messiers had done on this problem.

Mr. Rowe: He agreed about the handicap which the undercarriage represented in aircraft design, and that its elimination was a goal to work for, except possibly for aircraft making short hops where the handling time on the ground was an important factor in operating efficiency. He believed that development work should go on on these lines regardless for the present of the capital cost in providing the necessary equipment. Even an enormous expenditure on ground devices would be paid back by the improvement in payload. In this connection, the French A.F.I.T.A. was in the process of considering the matter and he would like to suggest that at some time in the near future, a meeting under the joint auspices of the R.Ae.S. and the A.F.I.T.A. could usefully exchange ideas on the problem.

There was a compromise to be sought between complete international standardisation and the international anarchy which existed at present. Many technical problems were, after all, the same in all countries and the separate realisations often differed only in minor detail sufficient completely to upset inter-changeability.

For this reason and as regards tyres, it seemed to him logical that the tyres on certain common aircraft which were likely to stay in service for some time could be adopted as an international standard; he felt also that such bodies as the R.Ae.S., I.Ae.S. and the A.F.I.T.A. should maintain contact so that in the future, new national standards for tyres should not be established differing only in minor detail the one from the other.

He was pleased that Mr. Rowe adopted the point of view about stressing cases for undercarriages, which he thought was the only one which would allow proper progress. No prototype should complete its tests without strain gauge and accelerometer recordings being taken to measure the loads on the undercarriage and its structure during landing, taxying, and so on. This would enable an accurate measure of the true forces being applied to the undercarriage to be arrived at.

taking into account the particular characteristics of the aircraft itself.

He appreciated Mr. Rowe's point of view about castoring wheels. The exploitation of private flying would involve the building of many landing grounds; a small increase in the weight of the aircraft would be offset by a reduction in upkeep costs of the landing grounds and the great economy which would result from the elimination of multiple landing strips. In addition, with private flying, operating efficiency was not of first importance. On the other hand, the position was different in the case of large transport aircraft which used the larger airports and whose higher landing speed reduced the severity of the side wind case. In these aircraft any complication of occasional utility involved a permanent penalty of payload.

The combination of castoring wheels on a retractable undercarriage with steering and means for locking on the ground, involved an appreciable penalty in the weight and cost.

The degree of co-operation between the aircraft and undercarriage designers was the function of the psychological confidence which existed between the designers themselves and required a complete mutual understanding.

The undercarriage maker should act more as a consulting engineer than as a mere supplier; in discussions of preliminary schemes the Messier Company had taken part in decisions which involved the structure itself. It was essential when an aircraft designer sacrificed the simplicity of the undercarriage for aerodynamic or structural reasons, that he should know what he was losing so that he was able to consider the pros and cons of the problem. In any event, they believed that the undercarriage maker, after accepting the data provided by the aircraft designer, should take the whole responsibility for the installation and testing of the prototype equipment and stress calculations.

It was difficult to reply exactly regarding the influence of the undercarriage travel on weight. They did know that long travels caused an appreciable percentage increase in the undercarriage weight and should, if possible, be avoided. As the surface of the ground was the same whatever the size of the aircraft, they did not consider it advisable to have less than 8 in. travel.

Pre-rotation would, they believed, become a necessity for large wheels. They had seen in the Goodyear Laboratory at Akron, Ohio, that tyres larger than those of the DC-6 would not stand those tests normally made on smaller sizes Rapid deterioration of the tread occurred. In addition, pre-rotation might allow an appreciable reduction in structure weight in certain cases if allowance could be made for the reduction in high drag load at touch-down.

It had been found in the U.S.A. that flaps on the sides of the tyres as the means for pre-rotation did not give sufficient speed. A hydraulic motor on the wheel was a good solution and should give good results, but with the general adoption of higher voltages, electrical pre-rotation might be preferred.

The helicopter undercarriage presented certain special problems of its own. While normal landings were comparatively light, an emergency landing might require appreciable energy absorption, although possibly at the expense of permanent damage to the undercarriage. On the other hand, the damping of rotor vibration was an important function of the undercarriage, this becoming more complicated if there were two rotors.

Mr. Tye: He was glad that the British Civil Airworthiness Requirements had been based on the I.C.A.O. conditions, but were they the same for military aircraft? There were several aircraft in every country which were being designed for both military and civil purposes with the same undercarriage. In France they hoped to get a single set of conditions with special additional cases where necessary. He did not agree with Mr. Tye on the fact that regulations were based on the worst aircraft. They must get to the stage where bad aircraft were not accepted and were ruthlessly eliminated if their operating characteristics were not satisfactory.

Mr. Stafford: *Locking of the nose wheel.* It was possible that in certain cases it might be necessary to lock the front wheel. They believed that a limited lock was essential so that excessive forces were not set up in the nose wheel. The system described in the paper enabled this pressure locking to be achieved at will and, should shimmy start to appear, it could soon be damped out. Whether pressure locking was, in fact, necessary depended largely on the characteristics of the aircraft and was probably mainly an aerodynamic problem.

Steering control. Steering over ±90° introduced mechanical difficulties in the steering mechanism. American practice up to the present had been to use a small angle for steering and to disengage the mechanism for ground manœuvring. The steering gear ratio must be sufficiently low geared for the easy control of the nose wheel at speed. Their own experience was not sufficient to give any definite information but they suggested that 20° wheel swivel for half a turn of the steering wheel should be satisfactory.

Braking. Mr. Stafford's interesting information confirmed the point made in the lecture that official requirements were often based on arbitrary suppositions without regard to existing practice. What they were trying to do in France, and why they had chosen a nominal speed of 100 m.p.h. from which brakes must stop the aircraft, was to find out by systematic tests on prototypes what degree of braking was required on a particular aircraft.

He had no information on the relative weights of disc and bag brakes. This would depend essentially on the temperature to which the discs or drums could be taken and the degree of cooling by direct dissipation to the atmosphere. He believed that disc brakes could reliably be taken to much higher temperatures than drums and that therefore they would be lighter. On the other hand, it was quite true that the bag brake as used in England was in itself, an extremely light mechanism, although it was essentially applied only to the drum type of brake.

Drag loads. As regards the drag loads due to spinning up the wheel, the French requirements were more severe than the American; for example, the radius rod for an aircraft of 33 tons at the moment in hand, would have to deal with 45 tons load to the French requirements and only 31 to the American. The Americans did not appear to consider their requirement insufficient. He had observed during a landing in a Vickers Viking that as the wheel touched the ground, the whole undercarriage frame bent backwards by what appeared to be at least half an inch. It seemed therefore that one must not minimise the importance of this type of drag load and that in the case of large aircraft, pre-rotation of the wheels might enable appreciable weight savings to be made. They had no knowledge in France of any systematic tests which had been made on this question to enable the actual magnitude of the drag loads to be checked. It was true, however, that the effect of the undercarriage telescopic friction must be important. In the case of the Halifax undercarriage the telescopic friction was lower than normal. They felt that on an undercarriage with appreciable telescopic friction the sticking of the undercarriage at the moment of touch-down aggravated the high drag load.

Professor Temple: Professor Temple's work on shimmy was known and appreciated in France.

Mr. Parker: They also had had considerable difficulties in France with light alloy castings. To enable them to get to the bottom of these difficulties they actually set up a small, but well equipped, experimental foundry. The objects of this foundry, apart from research on the alloys, was to determine the optimum conditions for the use of the castings themselves. The Service Technique made the following important decisions relating to prototype castings.

1. They accepted the responsibility for the development cost of the castings.
2. They specified three categories of castings, similar to the British Class 1, 2 and 3.
3. For each of these categories they determined test requirements and X-ray procedure. (Radiological examination of test pieces was made throughout production.)
4. The designer to give the foundry drawings showing the highly stressed areas and where test pieces were to be taken from.
5. The foundry to draw up a foundry specification sheet on which were given all the indications relating to the castings (such as moulding, coring, feeding, chills, and so on.)

He believed that with the proper organisation and the right foundry technique castings were extremely interesting for small or medium size undercarriages, especially when one examined the difficulties experienced with high tensile welded steel undercarriages, and the cost of using light alloy forgings.

Emergency operation. In France the most common emergency system was the use of a second hydraulic circuit fed from an independent pump, although the army was considering the use of mechanical emergency. He believed that both these systems were inefficient, because of the additional com-

plication introduced for something which was used occasionally. Emergency devices (compressed or liquid-air bottles, cartridges, and so on) mounted directly on the jacks and connected to the undercarriage mechanisms by, for example, cables, might enable savings in weight and complication to be made.

Undercarriage locking. Internal locks were very satisfactory when the undercarriage geometry was appropriate to their use. In other words, if the jack made an acute angle with the aligned radius rod a small movement of the jack corresponded to an appreciable misalignment of the radius rod and therefore the lock would not give the necessary security. In this case separate locks were necessary but preferably not operated by separate hydraulic circuits, jacks, and so on.

*The N.C.*701 undercarriage. The figures given in Fig. 15 were, in fact, calculated. It was possible that in the case of the castings the actual strength might be higher than calculated but this was unlikely in the case of the steel parts. The actual undercarriage shown weighed 115 lb. and a similar French undercarriage for an aircraft of the same weight (11,000 lb.) weighed 155 lb.

Mr. Woodford: They were very interested in the use of electricity and believed that the wider adoption of higher voltages would widen its application.

One must not dare the hydraulic engineer to do everything by hydraulics, even de-icing. Obviously he could not very well operate radio or radar, but he would get his revenge on the constant speed drive for the alternator.

It was a fact that electrical apparatus was not so reliable at high altitude as hydraulic equipment and required appreciable maintenance. For similar reasons hydraulic starting of road vehicles was becoming popular in France.

Mr. Petter: (1) He was sure that the increase in static load on the nose wheel would permit front wheel braking for the following reasons:

(a) Tests on the experimental Messier aeroplane which had brakes on the front wheel only gave conclusive results.
(b) The raising of nose wheel loading increased adherence, consequently avoiding the skidding of the front tyre which nullified steering and reduced variations in load due to the deceleration.

2. He was glad Mr. Petter was in favour of systematic tests to determine stressing cases.

3. The British designer would be wrong to doubt the results obtained with welded steel undercarriages in the U.S.A.; this process, however, required:—

(a) The proper selection and control of the steels.
(b) The use of flash welding with the proper jigs.
(c) Constant magnetic crack detection through all stages of the process.
(d) If forged and cast pieces were to be joined together, it was essential that they should be from the same material. Electric melting was the only means of getting the necessary high quality in the steels.

Arc- or gas-welded parts required skilled operators but flash-welded components were assembled in a machine and without skilled labour. Undercarriages of the type used on the DC-4 were produced in large quantities without difficulty.

He thought that the forged aluminium alloy solution was interesting and admired the main undercarriage of the Brabazon which used this construction. But the fact that one could not weld as with steel made this solution less flexible and might involve mechanical complications.

The use of high tensile cast steel was interesting but, unfortunately, in France they were not yet able to obtain results comparable with those achieved by the David Brown or Fischer Companies.

4. The proposal to standardise internationally five or six current dimensions of tyres was made to allow common types of commercial aircraft to have interchangeable tyres. There was no question of trying to restrict the development of prototypes.

Mr. Hoare: To brake all three wheels correctly he believed that it was necessary:

(1) To increase the static load on the front wheel to reduce the variations in this load under braking conditions and thus eliminate the risk of locking it.

2. Balance the loads between the three wheels by hydraulic interconnection.

3. To obtain the simultaneous contact of all three wheels with the ground by using aerodynamic devices which enabled the fuselage to be maintained horizontally.

They investigated these problems and developed certain solutions on the experimental Messier aeroplane with tandem undercarriage in 1934. It was possible to

control the brake by the deflection, or more properly, the pressure in the shock absorber. In 1934 they tested an aircraft fitted with a tail skid, the shock absorber of which acted hydraulically to apply the brakes. The results were excellent and enabled the aircraft to land in a distance 25 per cent. less than that normally obtained with the tail wheel type undercarriage, and this without any risk of skidding.

As regards Mr. Hoare's remarks about pre-rotation, to land with brakes on had been considered the most reprehensible practice for a number of years because of the rapid wear of tyres which ensued. With the higher landing speeds now becoming common such practice might lead to serious accidents. Safety devices to prevent this happening could be designed, but their complication might in turn lead to other difficulties.

The use of the potential energy of the aircraft to effect braking was possible as he had already mentioned above in connection with the tail skid system. But was it wise to complicate the duty of the shock absorber when there were already ample power sources available on board? In addition, as the brake must be able to operate at take-off, it would be necessary to store energy for this purpose which would introduce further complications.

Mr. Orloff: Mr. Orloff's remarks bore out his comments in the paper and in other parts of the discussion that official requirements were often drawn up rather arbitrarily.

Mr. Clarke: It was difficult to reply accurately to questions on the percentage of weight for the following reasons:—

Undercarriages were elements which differed widely from one aircraft to another, depending on whether the wing was high or low, on the number of engines, and so on.

It was also a fact that the weight of the undercarriage would vary considerably as a function of the ease with which it could be disposed in the aircraft. They had seen cases where they could save 1 per cent. of the aircraft weight by the redisposition of the undercarriage attachment points on the aircraft. In one case where the attachment points were fixed and badly chosen, they had reached the almost unbelievable weight of 11 per cent.

One could say that for a civil low-wing aircraft of 20 to 40 tons weight, the complete undercarriage with retraction gear, wheels, and so on, should weigh between 5½ per cent. and 7 per cent. and might be as much as 8 per cent. with high-wing aircraft. A tail wheel type undercarriage would save ½ per cent. to ¾ per cent. on these weights.

These figures were applicable for a shock absorber travel between 8 and 12 inches. Fully castoring undercarriages would certainly be heavier but they had no exact information at present.

Mr. Chaplin: It was true that the increase in specified vertical velocities had led to the use of long travels. This was no new problem for them because for more than 15 years they had been making shock absorbers with travels of 12 in. to 18 in. They had never been troubled by the aerodynamic instability of the nose wheel for the following reasons:—

(a) Almost always they used wheels with both static and dynamic stability which automatically were aerodynamically stable.

(b) They had always used a comparatively strong self-centring device to keep the wheel on the fore and aft plane when the shock absorber was extended.

They were glad that these two steps had kept them out of the difficulty mentioned by Mr. Chaplin and were grateful to him for bringing it to their attention.

He agreed with Mr. Chaplin's remarks about ordinary devices for aerodynamic braking, but if by some means involving most of the wing span they could simultaneously destroy the lift and increase the drag, he believed one could get excellent results. It seemed also, that the ground interference effect could be increased with flaps of this type.

Few pilots complained of the suspension of their shock absorbers; it was also true that the human body was not very sensitive to accelerations if they were nearly instantaneous, but the structure would record these accelerations faithfully and this was one of the origins of fatigue failure.

If a shock absorber were stressed for an acceleration factor close to the elastic limit under a particular vertical velocity, it was conceivable and not difficult to calculate that this speed could be exceeded by as much as 20 per cent. when passing over a bump. Because of the square law effect this meant that the actual load developed in the shock absorber might reach the ultimate strength of the structure. The schemes he had described in the lecture were complicated enough

and not particularly safe. On the other hand, he had tried to show that the tandem wheel solution would get over these difficulties.

The remarks on the increase in severity of strength requirements due to incidents with inefficient shock absorbers illustrated that shock absorber performance should always be calculated and then verified by test. Mr. Chaplin's remarks also underlined his own comments on the subject of the airborne drop test.

He was fortunate to obtain such good results with steel castings. In France they were not yet in this happy position.

The Heinkel undercarriage was made as indicated by Mr. Chaplain. They constructed it to complete a German aircraft being built in France after the war, in spite of the greatest difficulties in obtaining appropriate materials and with the heat treatment. It was largely a question of experience and they believed that this process was a good one provided that the necessary material and welding experience were available.

Oxidisation was a difficulty, and atomic hydrogen welding might be advantageous.

He agreed about the skid; in addition to its technical advantages it would perhaps bring a peace of mind to the undercarriage constructor that he certainly had not got at the moment.

THE ROYAL AERONAUTICAL SOCIETY

Paper received June 1947.

ENEMY JET HISTORY

by

D. R. MAGUIRE, M.A., Grad.R.Ae.S.

Mr. Maguire learned to fly with the Cambridge University Air Squadron in 1940, *while attending St. John's College, Cambridge. He served during the war with the R.A.F. as a pilot and from September* 1945 *to December* 1946 *was in charge of Experimental Flying at the Empire Central Flying School. From January to October* 1947 *he was employed in the Gas Turbine Engineering Department of Metropolitan Vickers Electrical Co. Ltd. and is now with the Research Department, Engine Division, of the Bristol Aeroplane Co. Ltd.*

1. INTRODUCTION

THIS paper gives details of the first flights of the German, Italian and Japanese jet-propelled aircraft and engines during the last war. Only gas turbine jet propulsion has been covered.

The information was derived from reports made by allied investigators after the collapse of the axis powers.

Some of the data was conflicting but that presented here is believed to be the most accurate available. The author will welcome any corrections or additions that he is offered.

The first flight in the world of a turbo-jet-propelled aircraft was made by the Heinkel He.178 on the 27th August 1939. Heinkel, however, failed to maintain the excellent lead that they had established.

The Italian Caproni-Campini C.C.2 is reputed to have made a first flight a year later, but there is no reliable information concerning it until the much-publicised delivery flight to the Italian Air Force Experimental Establishment at Guidonia in November 1941. The aircraft did not use a gas turbine but was propelled by a ducted fan driven by a piston engine.

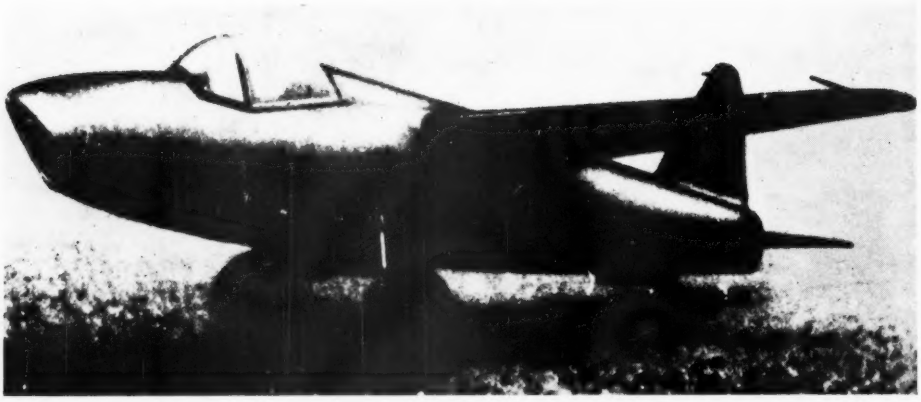
The Gloster-Whittle E28/39 flew first on the 14th May 1941 at last confirming Whittle's faith in the use of gas turbines for the jet propulsion of aircraft.

The Americans made their first jet flight in the Bell P.59A, Airacomet, on 1st October 1942.

Their own work being insufficiently advanced, the Japanese bought German licences and the Kikka, a copy of the Me.262, made its first flight on 6th August 1945.

This paper can give only the bare outlines of the enemy's work in this sphere.

Heinkel He.178.
The first jet-propelled aircraft to fly, on 27th August 1939, powered by a Heinkel S3, developing 900 lb. thrust.



The He.178 powered by a He.S3b.

Unfortunately, there is no information concerning the trials and tribulations of the engineers concerned.

2. GERMAN GAS TURBINE AERO-ENGINES

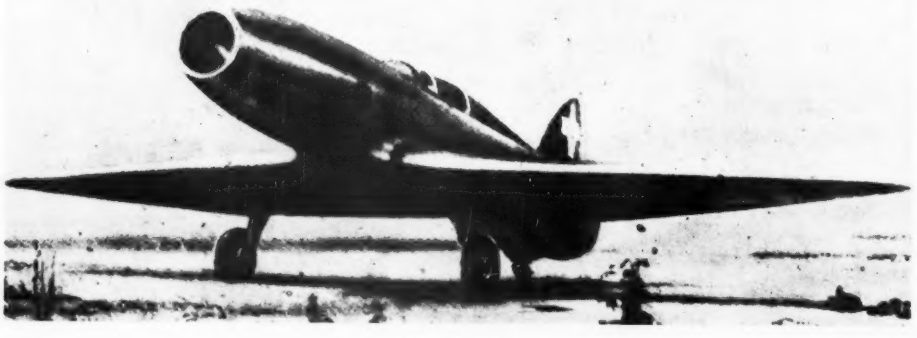
When he considered the propulsion of aircraft at high speeds, Dipl. Ing. Helmut Schelp of the German Air Ministry (R.L.M.) calculated that turbo-jet propulsion was necessary at aircraft speeds in excess of 500 m.p.h.

Accordingly in 1938 Schelp asked all the German aero-engine manufacturers to begin the design and development of turbo-jet engines. Dr. Oestrich of B.M.W. was keen, and Dr. Franz of Junkers agreed to do so. Daimler-Benz were frankly uninterested, while Heinkels objected strongly to any interference and refused to co-operate since they were jealous of losing their lead in this new field.

(*a*) HEINKEL

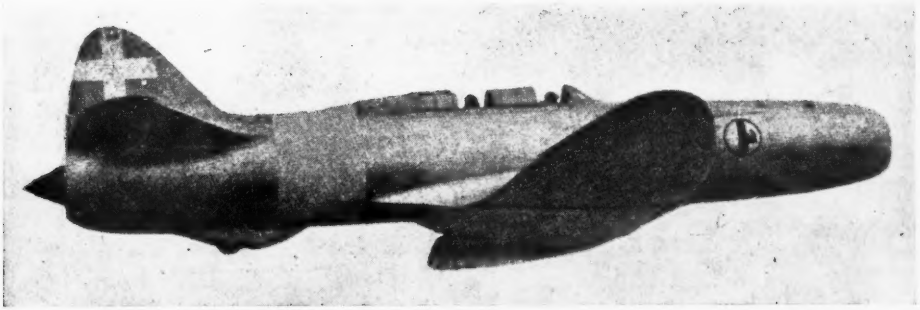
Heinkel began work on gas turbines when von Ohain joined them in 1936. On the 27th August 1939 the Heinkel He.178 aircraft made the first jet flight in history, powered by a Heinkel He.S3b gas turbine.

The He.S3 comprised an axial inducer and a centrifugal compressor driven by a radial inflow turbine. The combustion chamber was an annular reverse flow one, giving the engine a large overall diameter. Its specific fuel consumption was about 2 lb. of fuel per lb. of thrust per hour.



The C.C.2.

This view of the Campini machine on the ground shows the wing location below the fuselage which forms the main air duct.



The C.C.2.

The He.S6 was a development of the S3 to give 1,000 lb. of thrust.

From it was developed the He.S8, which differed in using a straight-through annular combustion chamber. This improved the combustion and reduced the overall diameter. In it were no less than 128 fuel injection nozzles. This engine received the R.L.M. designation 109-001.

The S10 was an S8, modified to drive a ducted fan in front of the compressor. This was to increase the thrust to 2,500 lb. at 500 m.p.h.

The preliminary studies of the He.S11, designated 109-011 by R.L.M., were concluded in September 1942 but work on it was never hurried. Although it was the most promising turbo-jet that the Germans possessed and was going into production, it had not become operational at the end of the war.

All the above engines were designed by von Ohain. In 1939 Mueller joined Heinkel after leaving Junkers. He favoured axial compressors and turbines and used them in his design of the He.S30, which bore a resemblance to the Jumo 004.

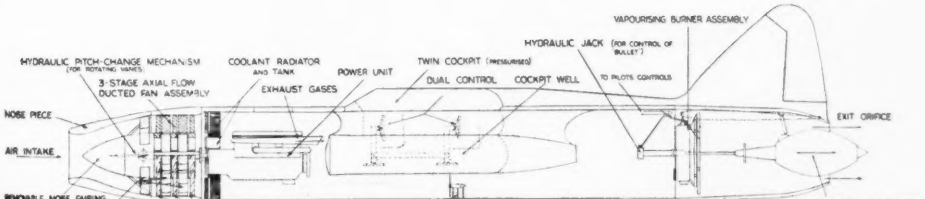
Next he developed the S40, which used constant volume combustion.

The S50d was a 24-cylinder diesel engine driving a ducted fan. The S50z used, similarly, a 16-cylinder X engine.

The S60 was a 32-cylinder X diesel engine driving a ducted fan. It utilised the energy of the exhaust gases in a radial inflow turbine coupled to the engine shaft.

None of these designs by Mueller was successful. In 1940 Heinkel acquired Hirth Motoren in order to expand the engine side of their firm. Later they were joined by Campini, the Italian jet designer.

Being jealous and secretive, Heinkel worked independently of R.L.M. although subsidised by them, until 1941 when they asked to join the pool of gas turbine firms and to share everyone's experience.


VAPOURISING BURNER ASSEMBLY
HYDRAULIC JACK (FOR CONTROL OF BULLET)
HYDRAULIC PITCH-CHANGE MECHANISM (FOR ROTATING VANES)
COOLANT RADIATOR AND TANK
POWER UNIT
TWIN COCKPIT (PRESSURISED)
3-STAGE AXIAL FLOW DUCTED FAN ASSEMBLY
EXHAUST GASES
DUAL CONTROL COCKPIT WELL
TO PILOTS CONTROLS
NOSE PIECE
EXIT ORIFICE
AIR INTAKE
REMOVABLE NOSE FAIRING
FIXED GUIDE VANES (PITCH ADJUSTABLE ON GROUND)
ROTATING VANES (DRIVEN BY ENGINE)
WINDMILL
FUSELAGE (DOUBLE SKIN THROUGHOUT)
ADJUSTABLE BULLET MOVES AXIALLY TO VARY EXIT ORIFICE AREA HYDRAULICALLY OPERATED SUPPORTED BY 3 STAYS (ONLY ONE SHOWN)
REAR FUSELAGE (HAS ADDITIONAL STAINLESS STEEL LINING)
RETRACTABLE UNDERCARRIAGE
RETRACTABLE TAIL-WHEEL
ALL-UP WEIGHT (TAKE-OFF) 9250 LBS.
SPAN 52 FT.
LENGTH 43 FT.
POWER UNIT 800 H.P. ISOTTA FRASCHINI ENGINE. 12 CYLINDER 'VEE' LIQUID COOLED.
CAPRONI–CAMPINI AIRCRAFT
DIAGRAMMATIC SECTION THROUGH FUSELAGE
SCALE

The C.C.2.

The He.280.

They had not profited from their early start and remained almost entirely on a research and development basis.

(*b*) JUNKERS

Junkers made their first gas turbine studies in 1936. These were concerned with free piston engines which, being far too heavy, were discarded.

In 1939, after R.L.M.'s request, Junkers began work on a half-size unit to furnish design data for the Jumo 004. This ran at 30,000 r.p.m. The turbine provided 400 s.h.p. to drive the compressor, which burst shortly after and was not rebuilt.

In August 1939 work began on the Jumo 004-A. The first was tested in December 1940 but was destroyed by a compressor stator blade failure. The reason for this took a long while to ascertain, so further units were not constructed until July 1941.

The engine made its initial flights suspended beneath a Messerschmitt Me.110 flying test bed in November 1941.

The prototype Messerschmitt Me.262 flew in June 1942, powered by two Jumo 004-A jets. The Jumo 004-B went into production and first powered the Me.262 in May 1943.

The Jumo 004-B was the jet engine most used by the German Air Force, since R.L.M. policy had been to get the 004 into production as soon as possible. The B.M.W.003 was developed to supersede it, and the He.S011 was being developed to a still more advanced state to succeed the 003.

Junkers had projected the Jumo 012 jet unit and a development of it, the 022 gas turbine driving a propeller. Neither progressed beyond the design stage.

(*c*) BAYERISCHE FLUGMOTORENBAU—B.M.W.

B.M.W. began some preliminary work on gas turbines, primarily for turbo-super-

The Me.262.

The Ar.234A.

chargers, in 1934. Later they considered an "M.L." unit. This was a piston engine driving a compressor or ducted fan. Afterburning in the air stream from the compressor was provided to increase the thrust, but this project was discarded.

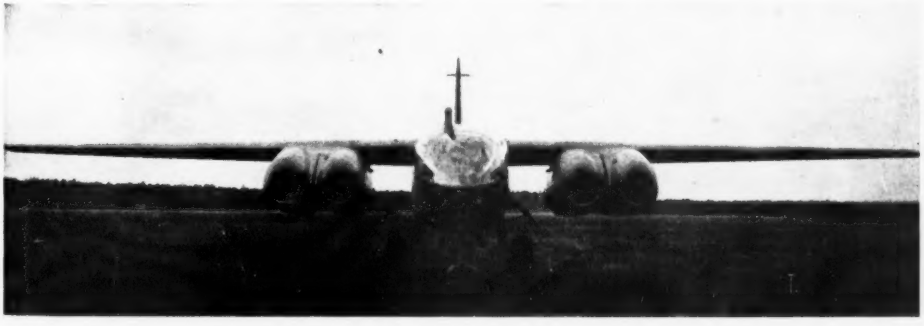
In 1939, after Schelp's approach, Dr. Oestrich and Dr. Wolfe began design studies of the P.3302. This ran first on the 20th February 1941, and gave only 330 lb. of thrust, which was most unsatisfactory. It was flight tested below an Me.110 and later in an Me.262 test bed, which had, in addition, a piston engine in the nose.

By August 1942 the 3302 was giving 1,300 lb. of thrust and finally was developed into the B.M.W. 003-A, which was first flight tested below a Ju.88 in October 1943. This Ju.88 was shot down later.

The 003-A2 went into large-scale production and was coming into service use in appreciable numbers at the end of the war.

Both B.M.W. and Junkers had obtained the design of their axial compressors from Dr. Encke and Dr. Beitz of Göttingen. These compressors were relatively inefficient so, in 1941, R.L.M. asked Dipl. Ing. Hermann Reuter of the Brown-Boveri Company to design a compressor to replace exactly that in the 003. This was to be completely interchangeable with the original compressor so as to avoid redesigning the remainder of the engine. Brown-Boveri supplied the Hermso I and II, which were fitted to the 003-C and increased the static thrust from 1,770 lb. to 1,990 lb.

B.M.W. started the design of the 018 jet unit in 1940, but work on it was so delayed by bombing that the prototype was never completed, although portions of it had been built and tested. By the addition of a fourth turbine stage it was to drive a counter



The Ar 234C-3.

GERMAN GAS TURBINES

Engine	Thrust and Propeller S.H.P.	Weight	Specific Fuel Consumption	Max. R.P.M.	Dia. Length	Compressor stages	Turbine stages	Combustion chamber(s)
HEINKEL								
He.S3	900 lb.	800 lb.	2	13,000	36.5 in. ——	1 axial 1 radial	1 radial inflow	annular reverse flow
He.S8	1,500 lb.	840 lb.		13,500	30.5 in. ——	1 axial 1 radial	1 radial inflow	annular
He.S10	1,500 lb.	1,100 lb.		13,500	64.5 in. ——	1 axial 1 radial	1 radial inflow	annular
He.S11	2,860 lb.	2,090 lb.	1.31	11,000	34.5 in. 11 ft. 6 in.	1 axial 1 radial 3 axial	1 axial	annular
B.M.W.								
003.A-2	1,770 lb.	1,250 lb.	1.47	9,500	27 in. 10 ft. 4 in.	7 axial	1 axial	annular
003.C-1	1,990 lb.	1,250 lb.		9,500	27 in. 9 ft. 10 in.	7 axial	1 axial	annular
018	7,500 lb.	5,100 lb	1.1	6,000	49 in. 13 ft. 9 in.	12 axial	3 axial	annular
028	7,000 h.p. + 3,000 lb.	7,700 lb.		6,000	49 in. 19 ft.	12 axial	4 axial	annular
3306	3,760 lb.	2,000 lb.			33 in. 10 ft. 6in.	7 axial	1 axial	annular
3307	1,100 lb.	1,450 lb.			27 in. 9 ft. 4 in.	7 axial	1 axial	——
JUNKERS								
Jumo 004B	1,890 lb.	1,590 lb.	1.4	8,700	31.5 in. 12 ft. 8 in.	8 axial	1 axial	6 cans
012	6,000 lb.	4,400 lb.	1.2		42 in. 17 ft.	11 axial	2 axial	6 cans or 1 annular
022	6,000 h.p.				38.5 in. 18 ft. 5 in.	11 axial	3 axial	6 cans or 1 annular
DAIMLER-BENZ								
007	2,650 lb.	3,000 lb.		12,500	34 in. 15 ft. 3 in.	17 axial (3 fan)	1 axial	4 or 5 cans

GERMAN TURBO-JET AIRCRAFT

Aircraft	Engines	Date of first flight	Top speed m.p.h.	Span	Length	Weight	Fuel capacity gallons
He.178	one He.S3b	27/8/39	250				
He.280	two He.S8	1941					
Me.262	two Jumo 004	18/6/42	525 at 30,000 ft.	41 ft.	34 ft. 9 in.	13,450 lb.	437
Ar.234	two Jumo 004	Nov. 1943	470 at 20,000 ft.	47 ft. 4 in.	41 ft. 7 in.	20,000 lb.	836
He.162	one B.M.W.003	6/12/44	520 at 20,000 ft.	23 ft. 8 in.	29 ft. 10 in.	5,940 lb.	208

He.S3b.

rotating propeller and was designated the 028.

B.M.W. also had in hand the design of the 3306. Generally it was to be similar, but larger and more efficient than the 003.

The 3307 was an expendable turbo-jet to drive projectiles like the V.1 flying bomb and it was to be very cheap to manufacture.

(*d*) DAIMLER-BENZ

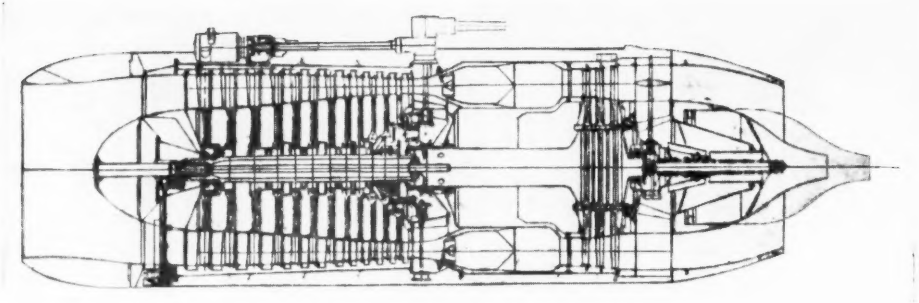
In 1941 Dr. Leist of Daimler-Benz designed the D-B.007, which used a counter-rotating axial compressor and ducted fan. The compressor casing carried the fan blading and rotated in the opposite direction to the rotor, to which it was geared. The prototype ran in the autumn of 1943 but was extremely complicated and heavy. R.L.M. stopped development work on it and set Daimler-Benz to adapt the Heinkel He.S011 to drive a propeller. This project was designated the 109-021.

3. GERMAN TURBO-JET AIRCRAFT

The Heinkel He.178 was the first jet aircraft ever to fly. It was a single-seater, high wing monoplane with a tail wheel undercarriage. The engine was installed in the fuselage behind the pilot, in a similar manner to that of the Gloster E.28/39.

The He.178 supplied the design data for the He.280 single-seater fighter, the prototype

He.S8.



109-018 turbo-jet unit

of which made its first twenty flights as a glider while awaiting the He.S8 engines with which it was to be powered. The first power flights were made in 1941. Only eight He.280s were built, as it gave a great deal of development trouble before it was dropped in favour of the Me.262.

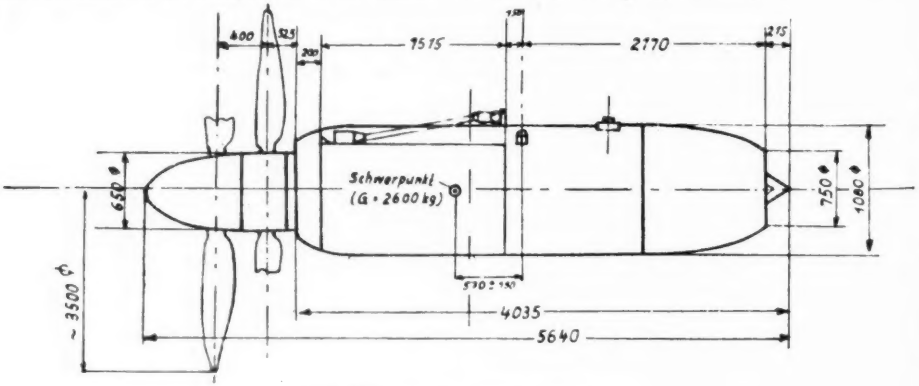
Messerschmitt began the design of the Me.262 in 1939 and it flew first in 1940 powered by a single Junkers 211 piston engine in the nose. In 1941 two He.S8 jets of 1,100 lb. thrust were fitted but the aircraft would not take off, and not until the 18th June 1942, with two Jumo 004-A jets installed, were the first flights made. The first three Me.262s had a tail wheel undercarriage. To get the tail up on take-off the use of brake was necessary during the run. All subsequent aircraft used a tricycle undercarriage.

The Arado 234 was designed in mid-1942 with a jettisonable undercarriage and landing skids, similar to the Me.163, and first flew in November 1943, but proved to be unsatisfactory. The Ar.234B-2 sub-type with a tricycle undercarriage flew first in December 1943, and went into production in June 1944, powered by two Jumo 004 jet units.

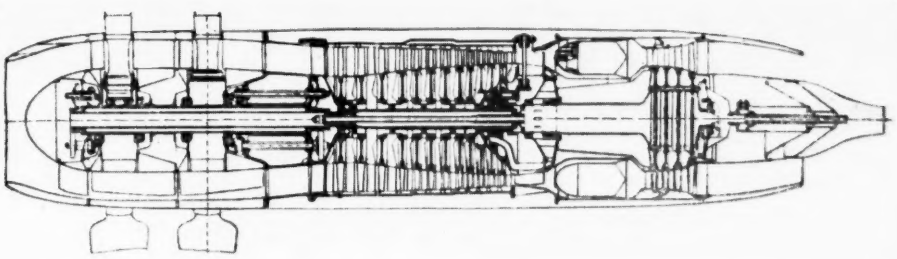
The aircraft carried a built-in parachute landing brake for use in emergency to reduce the landing run by half. It is particularly remarkable for the long range given it by a fuel tankage of 840 gallons.

Only nineteen of the Ar.234C-3 were built. This type was designed for high altitude reconnaissance, using a pressure cabin. The power units were four B.M.W.003 either spread along the wing or grouped in pairs.

Design of the Heinkel He.162 started on the 23rd September 1944 and the prototype made its first flight on the 6th December 1944—a record for high-speed design and construction. The aircraft went into production immediately, in spite of a structural defect in the wing which killed a number of test pilots. This defect was investigated by towing a full-size aircraft through a water tank to obtain a full-scale Reynolds number.



109-022 propeller-turbo-jet unit.



109-028 propeller-turbo-jet unit.

Apparently the Germans appreciated the value of jet propulsion for aircraft before the Allies, so they rushed their engines and aircraft into production before they were developed to a reliable state. Their shortage of raw materials and the movements and dispersal necessitated by bombing, retarded considerably the development and production of both engines and aircraft.

4. THE ITALIAN CAPRONI-CAMPINI AIRCRAFT

There appears to be no reliable information concerning Campini's work prior to the much-publicised delivery flight of the C.C.2 in November 1941 to Guidonia, for flight trials by the Italian Air Force. The aircraft gave continuous trouble and its performance was extremely unsatisfactory as the following figures show: :—

All-up weight: 9,250 lb. Span: 52 ft. Length 43 ft.
Power unit: 900 h.p. Isotta Fraschini liquid-cooled piston engine driving a 3-stage, variable pitch ducted fan.
Control: Pilot could vary pitch of ducted fan rotor blades and position of tail bullet.
After-burning was fitted in the tail pipe. Its use was necessary for take-off.
Fuel consumption: Piston engine: 70 g.p.h.
After-burning: 330 g.p.h.
Speed: less burners, 205 m.p.h. at 9,800 ft.
with burners, 233 m.p.h. at 9,800 ft.
less burners, 196 m.p.h. at 13,000 ft.
Length of take-off run: 840 yds.
Initial rate of climb: 138 ft./min.
Mean rate of climb with burners: 364 ft./min.
Mean rate of climb less burners: 288 ft./min.

Campini was over-optimistic of the efficacy of piston engine-driven ducted fans for aircraft propulsion. Besides the C.C.2 which flew, he had made a number of designs for modifications to existing fighters and bombers. None got very far.

Campini submitted a design for a gas turbine to drive a propeller, but this does not bear investigation.

He had little support at the Italian Air Ministry, but some advantage with Mussolini. Unfortunately there are few traces of his early work.

5. JAPANESE JETS

The Japanese had done preliminary work on compressors and combustion and a little on turbines, with marked lack of success. They had used various piston engines to drive a compressor with, and without, after-burning to increase the jet thrust.

One such project used a Kinsei 60 radial engine of 1,580 h.p. to drive a compressor with after-burning. It was 5 ft. in diameter and 12 ft. long and was designed to give more than 2,000 lb. of thrust.

A similar design was the TSU.11 which used a Hatsukaze four-cylinder inverted engine of 130 h.p. to drive the compressor, providing 350 lb. thrust. This engine was fitted to the Oka. II or Baka Mk. II suicide fighter instead of the rocket propulsion of the Mk. I. The prototype flew in June 1945 but crashed on landing.

The licence to build the B.M.W.003 was sold to Japan for 20,000,000 reichsmarks and workshop drawings were shipped to Japan by submarine in November 1944. Various firms were set to build the 003 but the Navy were the only people to succeed and by the end of the war they had built ten or twenty. It was designated the NE.20 but gave only 880 lb. of thrust, half that of the B.M.W.003, and was to be used in the Oka III or Baka Mk. III.

The Kikka was a copy of the Me.262. Powered by two NE.20s it is supposed to have made its first successful flight, of 21 minutes, on the 6th August 1945. Because it was so under-powered rocket-assisted take-off was used on the first flight. The aerodrome from which the test flight was made was on the coast and the pilot took-off over the sea. When the rockets had burnt out the thrust suddenly decreased, causing the pilot to think his engine had failed; he switched off and ditched the aircraft.

The Japanese had also copied the Me.163, but their prototype had made only a few flights before the end of the war.

The Japanese copied the German information they received too late but achieved nothing of note thereby, or on their own.

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REVIEW

Proceedings of the Society for Experimental Stress Analysis Vol. IV, No. 2. Published by Addison - Wesley Press Inc., Kendell Square Building, Cambridge 42, Mass. Price 6 Dollars.

The production of this latest volume maintains the high standard one has come to expect. The first half of the volume contains articles on fatigue and dynamic effects in general, while the second half deals mainly with measuring instruments and the telemetering of the data obtained by such instruments. Separating these two groups of articles is a paper on rotor blade analysis.

The first paper describes an investigation on fatigue tests in major aircraft structural components. The weakest link in the experiments is the assessment of the applied dynamic loads (such as gust loads). This is probably because of the rather nebulous nature of knowledge on gust effects, a fault which appears in most papers on this subject. The actual experiments are excellently set up and described.

There follows an interesting article on some experiments to check an analytical formula for stress-strain in the plastic range. Excellent agreement has been found with interesting exceptions for several commonly used materials.

The difficulty of detecting visually, fatigue cracks is well known and in the next paper an experimental method is given to determine these cracks by electrical means. Thin copper wires included in electrical circuits are cemented to the structure. The wire is ruptured at fatigue cracks and the resulting break in the circuit draws attention to the crack.

A hydraulic machine for fatigue testing of engine components is described in the next article. The machine is very versatile with a capacity of 50 tons at frequencies up to 2,000 cycles a minute.

A plea for more attention to the avoidance of "stress raisers during the detail design" of aircraft components is made in the following paper. Examples of premature fatigue failure which were avoided with redesign are given.

Extravagant language and a series of obscure statements on obvious truths characterise an article on stress analysis utilisation in dynamic testing.

A successful method to maintain continuous electrical connection between stationary and rapidly oscillating bodies is well described in the following paper.

There is now available a large literature on the stresses and deformation of rotor blades under steady loads. The next paper describes experiments on a structural model to check the various analytical methods. The step-by-step method is found to be the most accurate. Interesting is the inaccuracy of the energy and collocation methods.

The series of articles on measuring instruments and telemetering begins with a paper on the reluctance gauge. Various applications of such gauges are discussed and their main advantage in comparison with resistance strain gauges is stated to be the high signal output which facilitates radio telemetering when installation weight is critical.

Yet another device to record small movements or forces by electrical means is described in an article on the differential transformer. One instrument described has a sensitivity of 15 volts per 0.001 in. displacement.

In the following paper the general principles of spring-mass accelerometers in electro-mechanical transducers are discussed. The desirable characteristics of such instruments are indicated for various applications. An elementary account of the mathematical theory is given in an appendix.

The final paper describes the equipment developed at the Curtiss-Wright Corporation and the Cornell Aeronautical Laboratory for telemetering flight test measurements by means of radio and television, and gives the impression that the experiments described constitute a substantial contribution to knowledge on this subject.

The titles of the papers are as follows:—

"Fatigue Tests of Major Aircraft Structural Components," by W. G. Pierpont.

"Precision Determination of Stress-Strain Curves in the Plastic Range," by John R. Low, Jr. and Frank Garofalo.

"A Method of Detecting Incipient Fatigue Failure," by Henry W. Foster.

"A Machine for Fatigue Testing Full-Size Parts," by A. F. Underwood and C. B. Griffin.

"Some Repeated Load Investigations on Aircraft Components," by S. A. Gordon.

"Stress Analysis Utilisation in Dynamic Testing," by Roy W. Brown.

"Device for Maintaining Continuous Electrical Connections with Reciprocating Engine Parts," by W. A. Wallace and W. A. Casler.

"Evaluation of Various Methods of Rotor-Blade Analysis by Means of a Structural Model," by Robert Mayne.

"Reluctance Gages for Telemetering Strain Data," by W. H. Pickering.

"The Linear Variable Differential Transformer," by Herman Schaevitz.

"Design and Application of Accelerometers," by David E. Weiss.

"Aircraft Instruments for Radio-Telemetering and Television-Telemetering," by Carl L. Frederick.

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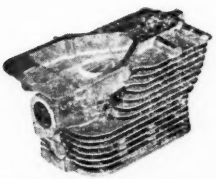

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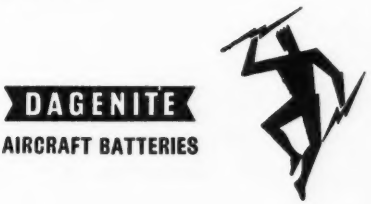

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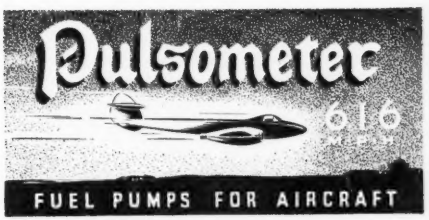

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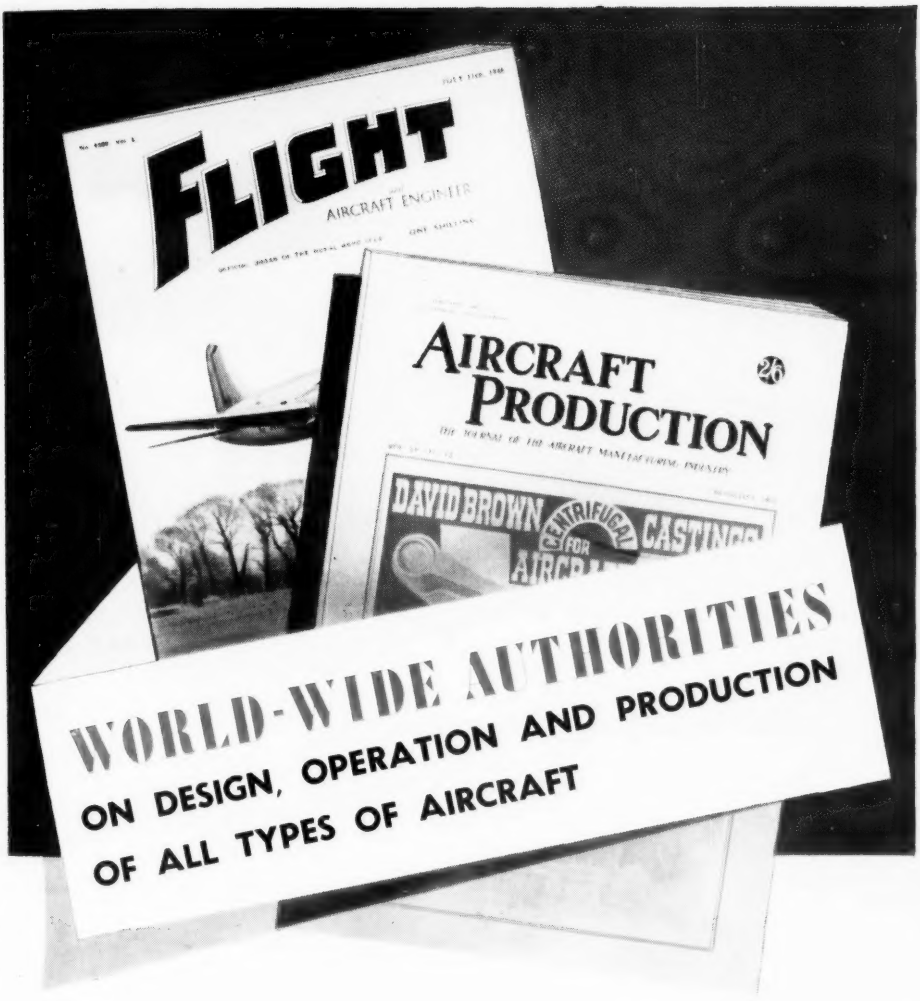

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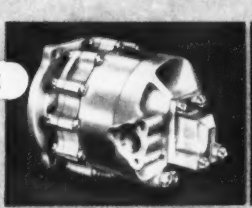

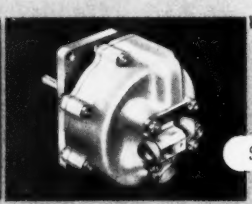

SINGLE

Dowty Fuel Pumps deliver 600 to 1,320 Imperial gallons per hour at 3,500 r.p.m. and 1,000 lbs. per square inch pressure

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